



**AN INVESTIGATION AND ANALYSIS OF THE VESTIBULO-OCULAR
REFLEX (VOR) IN A VIBRATION ENVIRONMENT**

THESIS

Daniel J. Uribe, Second Lieutenant, USAF

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**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Daniel J. Uribe, BS

Second Lieutenant, USAF

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Daniel J. Uribe, BS
Second Lieutenant, USAF

Approved:

Michael Miller, PhD (Chairman)

Date

Suzanne Smith, PhD (Member)

Date

John Colombi, PhD (Member)

Date

Abstract

Forty years of innovations have greatly improved Helmet-Mounted Displays (HMDs) and their integration into military systems. However, a significant issue with HMDs is the effect of vibration and the associated Vestibulo-Ocular Reflex (VOR). When a human's head is subject to low-frequency vibration, the VOR stabilizes the eye with respect to objects in the external environment. However, this response is inappropriate in HMDs as the display moves with the user's head and the VOR blurs the image as it is projected on the human retina. Current compensation techniques suggest increasing the size of displayed graphics or text to compensate for the loss of perceived resolution, which reduces the benefit of advanced high-definition HMDs. While limited research has been done on the VOR in real world settings, this research sought to understand and describe the VOR in the presence of head slued imagery as a function of whole body low-frequency vibration. An experimental HMD was designed and developed to allow a user to perform visual tasks, while also recording and tracking eye movements via video recording and EOG. A human subject experiment was executed to collect initial data on the effect of vibration on eye movements while performing simple tasks chosen to isolate specific eye motions. The results indicate that when fixating on a stationary target, the magnitude of eye movement was greatest at 4-6 Hz of, before steadily decreasing beyond this range. The addition of motion to this target increased the magnitude at 4-6 Hz. The findings are consistent with previous research, which has found a decline in visual performance in this frequency range.

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AN INVESTIGATION AND ANALYSIS OF THE VESTIBULO-OCULAR REFLEX IN A VIBRATION ENVIRONMENT

Chapter 1 - Introduction

1.1 General Issue

Helmet-Mounted Displays (HMDs) have become more prevalent over the past decade and they continue to improve and advance in terms of technology and operational application. For example, F-35 pilots rely completely on their HMD as all of their critical flight information is now displayed within the helmet since the traditional Heads Up Displays (HUDs) or panel displays employed in previous military aircraft are not employed in the F-35 cockpit. HMDs have also become a necessary component of the human interface within many Army helicopter platforms. Not only are HMDs being used in all types of aircraft, but smaller HMDs are being used by special operations personnel driving All Terrain Vehicles (ATVs) or other land based vehicles. HMDs offer excellent advantages in terms of task performance, such as missile targeting, but can also display information, which is instantaneously available to the user to improve overall performance by enhancing situational awareness.

While HMDs have provided positive improvements in aircrew and battlefield performance, many significant issues remain with this technology. One such issue occurs when these displays are viewed by an operator in a low-frequency vibration environment, defined as 10 Hz and below. Under these conditions the effectiveness of the HMD decreases sharply due to a loss in perceived resolution that is thought to occur as a result of the human Vestibulo-Ocular Reflex (VOR). When the head is subject to any motion,

the VOR attempts to move the eye in an equal magnitude and opposite direction to stabilize the line-of-sight to objects viewed within the natural environment. While this reflex is essential to our everyday lives, this reflex is detrimental to HMD use since the viewed object or image is moving with the head. As a result, the high-resolution display and information displayed upon it is perceived to be blurred, as the relative motion between the eye and the display blurs the image of the display on the human retina, reducing or precluding the legibility of the information on the display. This relative motion of the eye with respect to the display degrades any advantage the HMD may have provided the user, particularly if the user is reliant on the information displayed on the HMD. While most fixed wing jet-propelled aircraft are not subject to these low-frequency regimes for significant lengths of time, propeller driven aircraft occupants, helicopter operators, and land vehicles drivers can routinely experience low-frequency vibration during a mission. Further, certain fixed-wing jet aircraft are subject to buffeting which can expose the pilot to similar vibration, although for relatively short intervals of time. Even if the vibration and the associated VOR movement occurs for only a few seconds, the ability to performance during those few seconds in a highly dynamic and lethal battlefield could be the difference between locking onto and destroying a target verses a serious mishap.

1.2 Problem Statement

While the severity of human performance issues with HMDs associated with vibration in aircraft is well documented in the HMD literature, there remains a need for

an improved understanding of the mechanisms in order to develop better solutions to this issue. The long term, overall goal of this research endeavor seeks to delve deeper into HMD performance issues associated with vibration to determine how human performance with HMDs can be improved by stabilizing the image of an HMD with respect to the human eye. For instance, one might envision a system wherein a camera mounted on or within an HMD is used to monitor the position and orientation of the human eye with respect to the helmet as the user undergoes vibration. A video processor might then be used to leverage this information to predict the motion of the eye with respect to the display and adjust the video signal to stabilize the image provided by the HMD on the user's retina. The goal of this thesis is to investigate a series of specific questions, which must be addressed to understand the feasibility of this concept.

1.3 Research Objectives/Questions/Hypotheses

This research project concentrates on understanding the effect of the VOR for a user of an HMD while undergoing simple, z-axis sinusoidal vibration of known frequency and magnitude. To accomplish the overall research goal of improving human performance when using an HMD, there are several sub-objectives to consider, including the following:

- Isolate and analyze the VOR effect when performing simple tasks with an HMD in a simple vibration environment to establish a baseline understanding of the mechanism.

- Use the eye movement data to form initial predictive algorithms of eye position that can be used for image compensation in HMDs.
- With an established baseline, analyze the VOR and compensation algorithms in a multi-axis, real-world vibration environment to determine whether the VOR can be successfully measured and characterized in a complex setting and if the algorithms are feasible and predictable.

Based on previous VOR and vibration research, as well as real-world performance reports, there are some hypotheses that can be made regarding the outcome of this study:

- Eye movements and the VOR can be successfully tracked and analyzed within a vibration environment with an eye tracking apparatus and electro-oculography (EOG)
- The VOR will be effective in producing compensatory eye movements but in a certain frequency range (4-8 Hz), the compensation effectiveness (the gain and phase unity) will drop significantly, before becoming more effective at higher frequencies as the body better dampens higher frequency vibrations.
- The VOR effect will be more degrading in a tracking task, as opposed to a fixation task due to increased complexity in eye movement.
- Once eye movements and the VOR are successfully tracked, algorithms and hardware can be developed to provide HMD image compensation.

1.4 Research Focus

Given the complexity and length of the proposed research goal, the focus of this study was on establishing a baseline of eye motion relative to head motion, specifically by isolating and analyzing the VOR effect. This was done by simplifying the effects of real-world vibration environments by focusing on low-frequency, sinusoidal vibration in only one direction (z-axis), while introducing low-level, simple viewing and tracking tasks.

1.5 Investigative Questions

To meet the focus of this study, the research was designed to answer the following questions:

- What equipment can be used to track and analyze the VOR?
- How can the VOR be isolated within a simplified vibration environment?
- Is it possible that the VOR can be characterized to establish a baseline for future research in more complex settings?
- To what extent is the VOR predicable for use in compensation algorithms?

1.6 Methodology

The data for this research was collected by testing human subjects on a single-axis (z-axis) vibration table and exposing them to a range of low-frequency, sinusoidal vibration within a range, which has been documented to have the largest impact on human visual performance. The subjects were equipped with an HMD and were asked to perform simple viewing and tracking tasks while exposed to vibration. Digital video of

one of the user's eyes was illuminated with an infrared diode and recorded using a helmet-mounted camera configured to facilitate eye tracking. Additionally, electro-oculography (EOG) was employed to monitor the movement of the eye with respect to the head through the use of electrodes attached to the subject. The data was then processed and analyzed and the results and findings are discussed in later chapters of this thesis.

1.7 Assumptions/Limitations

This study served as the first step in a longer-term research project and therefore, was limited because of many simplifying assumptions. First, the study was conducted on a single-axis (z-axis) vibration table, using sinusoidal vibration frequencies. While much of the degradation of HMD performance occurs in the vertical direction, real-world vibration environments are much more complex, being multi-axis and composed of a complex combination of numerous frequencies. Thus, it is difficult to generalize the results of single-axis tests to that of the more complex domain. Additionally, this study was constrained to exposing the subjects to five specific frequencies, one at a time, which does not reflect the variability of a real-world flight regime. Finally, while it is assumed that the results from the human subjects can be generally applied, vibration effects are dependent on many factors to include body type and posture, which can vary greatly depending on the subjects.

1.8 Implications

Current compensation techniques rely on algorithms with multiple inputs collected from the physical environment in which the human is positioned and assume that the VOR perfectly compensates for environmental vibration. These compensation techniques have been inaccurate and latent. As a result, the primary method for addressing this issue is to increase the text/graphic size, which defeats the purpose of a high-resolution, detail-oriented display. The long term and overall research goal is to create an image stabilization algorithm based directly on the predication of the movement of the eye. If the VOR can be characterized and used as an input signal, then this algorithm and technique could be applied to existing and future HMDs to not only stabilize an image in the low-frequency vibration ranges, but also compensate for any vibration movement. A stable displayed image means that it doesn't matter how harsh the environment (buffet regime, rotary aircraft, rough land terrain), the user will still be able to access, read, and rely on the information from the HMD and preserve situational awareness and task performance. At a minimum, this research study will provide a deeper insight into the VOR and its behavior in a real-world environment, a topic that has been largely overlooked in the published literature.

1.9 Preview

Following this introduction and overview of this research is a review of the literature discussing HMDs, vibration effects, and the VOR. Chapter 3 is a description of the experimental method, the experimental apparatus that was established to collect the

data, and the data collection procedure. Chapter 4 is an analysis based on the findings from the data collected and Chapter 5 offers recommendations and conclusions based on these findings.

Chapter 2 - Literature Review

2.1 Chapter Overview

With the increased prevalence of HMDs in military and commercial use, numerous studies have been undertaken to continually improve the systems. The studies have focused on various aspects of the system: the biomechanics and the effect of an HMD on the human physically, issues with the HMD system itself, in terms of analyzing both its component and/or software, and of course the pursuit to maximize human performance while employing an HMD in real-world scenarios.

Additionally, many studies have analyzed the effects of vibration on humans. These studies have investigated medical and biological impacts, again as well as impacts on human performance. The Vestibulo-Ocular Reflex (VOR) specifically has only generally been examined from a medical perspective.

This chapter brings together and summarizes the most relevant research in the areas of HMDs, vibration, and the VOR in an effort to provide a foundation for an investigation and analysis of the VOR, while utilizing an HMD in a vibration environment.

2.2 Helmet Mounted Displays

2.2.1 History

In the 1970's, the Department of Defense (DOD) began initial research and development efforts into the use of an HMD in aircraft. This early endeavor focused on the Visual Target Acquisition System (VTAS), which allowed the pilot to target an

enemy aircraft and fire a missile by locking on to it visually, instead of relying on the traditional point-nose-shoot method. However, the program did not succeed as the missile technology had not advanced enough to allow for an off-boresight shot (Dornheim, 1995). However, a decade later, Air Force intelligence officials, analyzing the Soviet Union MIG-29's were troubled by a system they found on their pilots and aircraft. The Soviets were employing a helmet-mounted sight (HMS), which accomplished the goal of the failed VTAS. This technology had the potential to alter the landscape of air combat, tilting the favor towards the Soviets in the midst of the Cold War. This led to a renewed emphasis in HMD development in the 1980's, which has continued and increased over the last several years (Daetz, 2000).

2.2.2 HMD Advancements

Forty years of innovations have produced HMDs with higher resolution, greater readability in daylight conditions and color displays. HMDs have been successfully integrated into the cockpits of fighter and attack aircraft, which has improved integration of the human operator with the power of their weapons platform. Of particular military importance is the incorporation of the HMD into an aircraft's weapon system, allowing a pilot to track and destroy a target by pointing his head at and locking onto the target via the HMD. This capability greatly increases the envelope ($\pm 90^\circ$ off-boresight or greater depending on weapon capability) in which a pilot can successfully engage an adversary, offering a significant advantage over traditional systems which require the pilot to put the target within the aircraft radar limits ($\pm 60^\circ$) or pointing the forward nose of the aircraft at the target to fire. An HMD offers an obvious advantage, especially in the air-to-air

realm, but with improvement in weapon technology, these same capabilities have been applied in air-to-ground attacks as well (Daetz, 2000). Studies have also found that HMDs increase mobility because of the advantage of having critical data collimated for viewing wherever the head may be located during a task (Geiselman and Havig, 2010). This constant availability of data has been shown to increase operator situational awareness (Velger, 1998) and is central to the human interface for current and future aircraft, including the Joint Strike Fighter. In fact, this aircraft relies on the HMD to eliminate practically all other in-aircraft displays, reducing weight and power requirements, as well as providing novel capabilities, such as the ability to “look through” the hull of the aircraft below the canopy (“JSF”, 2003).

2.2.3 Current HMD Issues

While HMDs have provided positive improvements in aircrew performance, there are still many issues regarding symbology, color, and virtual design (Geiselman and Havig, 2010). Studies from a psychological perspective have found issues with visual clutter, attentional capture, and inattention blindness that can occur from using bright, collimated displays, such as HMDs (Gibb, 2010). Another key factor in degradation of performance when using HMDs, and often cited in HMD research, is vibration and the associated effects of the Vestibulo-Ocular Reflex (VOR) (Rash, et al, 2009).

2.3 Vibration

2.3.1 Overview

Vibration is part of many different types of environments and is something experienced every day, although we are not always consciously aware of its presence. For example, as one drives down the road, they are subject to various vibration frequencies coming from the engine or the road surface. Similarly, vibration occurs in aircraft, but at a higher intensity, especially in rotary-type aircraft. Vibration acts in a six-degree of freedom model meaning that it occurs in the x, y and z dimensions as well in roll, pitch and yaw. The transmission of aircraft vibration to the occupant is also highly dependent on many different variables which include, but are not limited to, aircraft type, seat type, body size, muscle tone, posture and helmet weight (Daetz, 2000).

2.3.2 Effects on the Human Body

The human body is physically sensitive to vibration, including the more intense exposures generated by military aircraft. Numerous studies have established that whole-body resonance occurs within the frequency range of 4 and 8 Hz during exposure to vertical vibration (ISO 2631-1: 1997). Research has shown that the transmission of vibration in the vicinity of resonance also produces relatively high pitch motions of the head primarily due to vibration in the vertical axis. (Paddan and Griffin, 1988). Head translational and rotational transmissibilities are generally greatest between 0-10 Hz, while most vibration occurring at higher frequencies beyond whole-body resonance (> 10 Hz) is typically dampened before reaching the head. Head pitch magnitude occurs most severely ($> 12 \text{ ms}^{-2}$) between 4-8 Hz as a result of the forces, which occur during

resonance (Smith, et al, 2007). The focus of this study will be to understand the effects of vibration on HMD use in this critical 0-10 Hz regime.

2.3.3 Effects on Human Performance

Studies have found that vibration degrades human performance as measured in terms of visual and task performance. When subjects seated in a vibrating helicopter seat were asked to read from a display, reading performance was degraded most severely for frequencies between 5-11 Hz, resulting in up to 20% error rates for the average human subject (Lewis & Griffin, 1980). A separate study, in which participants were subject to display-only, participant-only, and both display-participant vibration, found that the reading performance of the display-only vibration test rated significantly worse than the other two (Moseley & Griffin, 1987). These vibration effects also extended to more complex tasks associated with military operations. Early vibration studies found that the errors associated with the tracking of a target with both the eyes and the head increased nearly linearly with increased vibration amplitude when studied from 2-20 Hz (Shoenberger, 1972). In general, the highest or most severe visual performance degradation occurs at frequencies in which there is the highest vibration transmission to the head. While various research studies have demonstrated that the frequency range of the most severe performance degradation is 4-6 Hz, at a magnitude of 1 m/s^2 or .1 g, this research has also shown that visual performance can be adversely impacted at higher frequencies up to 20 Hz (Rash, 2009; Velger, 1998; Griffin, 1990).

2.4 The Human Eye

2.4.1 *Eye Motion*

The main culprit for the degradation of visual acuity and thus task performance due to vibration is the eye and the associated motions caused by vibration. The human eye generally moves in fast saccadic movements between relatively stable fixation points. Once fixated on a point, the human eye then time integrates information from the scene to obtain information. Therefore eye movements generally consist of a sequence of movements, each movement followed by a stationary interval during which the eye focuses on a point of interest. An alternate behavior occurs when a user is tracking a moving object such as a finger in front of their face or an enemy aircraft. During these events, the eye moves in smooth pursuit, often referred to as fixation reflex. During these eye movements, the eye is fixated on an object of interest and follows this object in space, typically without the need for any head movement. However, for fast moving objects, smooth pursuit eye movements can be coordinated with slow head movements to permit the object to be tracked over large distances. Importantly for either type of eye movement, the eye time-integrates the information from the scene, permitting the object of interest to be imaged onto the retina and captured at a high signal to noise ratio.

2.4.2 *The Vestibulo-Ocular Reflex (VOR)*

When rotational (roll, pitch and yaw) head movements, such as those caused by vibration, are introduced to the visual system, the eye responds with a reaction known as the vestibulo-ocular reflex (VOR). The VOR occurs when the semicircular canals in the ear detect head motion, sending a signal to the eye muscle, which induces the eye to

involuntarily move in the direction opposite to and near the same magnitude as the movement of the head. Studies have found the VOR to be effective only at frequencies up to 10 Hz, though other research suggests that the VOR is operative in frequency regimes of 20 Hz and higher (Griffin, 1990). This reflex allows whatever image is being focused on, to remain in the center of the retina while the head undergoes motion, facilitating the integration of information from the image. This reflex is most noticeable when doing high-impact activities such as running or jumping. During these activities, the VOR allows the world around us to be stabilized in space by moving our eyes to adjust for head motion and allowing us to fixate on objects within our environment. However, the VOR is not effective in the presence of translational head motion, because this head motion causes an angular displacement of the image, which is dependent upon the distance of the object from the eye, which the VOR cannot correct (Griffin, 1990). Additionally, eye resonance may occur in the presence of higher frequency vibration between 20 and 70 Hz, which has been found to cause significant blurring (Griffin, 1990). Though the scope of this research will focus on lower frequency ranges, resonance of structures within the human eye should be considered when discussing performance in the 20 to 70 Hz regime.

2.4.3 *The VOR and HMDs*

The VOR assumes that our natural world is stationary and we move within the world reference frame. Therefore, when visual information is provided on an HMD that moves with the head, this VOR response becomes inappropriate as the image provided by the HMD is stabilized with respect to the head. Since the VOR causes the eye to move to

compensate for head movement, this compensatory eye movement results in relative motion of the display with respect to the eye. This movement is similar to the motion that would occur if a person were sitting still in a chair and attempting to read a display in front of them that was vibrating, which previously stated research has indicated causes significant performance degradation.

Another complicating factor is that it cannot be assumed that the VOR correctly compensates for head motion under all circumstances. The pursuit, or fixation reflex, allows the eye to follow the data or text at vibrations at around 1 Hz, but at frequencies higher than 3 Hz, reading the vibrating display isn't only difficult, it becomes nearly impossible as the fixation reflex can no longer keep up with this movement (Griffin, 1990). Therefore, it is believed that the VOR induces relative motion between the HMD and the human retina that is not predictable. Unfortunately, while the VOR is an essential part of our human composition, when viewing HMDs at a low frequency range of less than 10 Hz, it can cause significant degradation in performance at the vibration frequencies previously specified and this degradation may not be predicted by measuring the motion of the user's head alone. Further, the head is not likely to vibrate synchronously with the environment as the human skeleton and tissue is likely to affect the transmission of vibration from an environment to the user's head.

2.5 Vibration Compensation

2.5.1 *Increased graphic size*

While vibration and the associated VOR effect are well documented, little has been done in the past 40 years to compensate for this effect. The rudimentary solution has been to simply increase the size of the text or graphics (Griffin & Lewis, 1978), space out the text (Griffin, McLeod, Moseley & Lewis, 1986) or change contrast levels (Moseley & Griffin, 1987) on the display. Each of the cited studies has found that these adjustments result in improved reading performance under vibration conditions. Unfortunately, these recommendations run counter to current technology investment in HMD technology, which furthers the resolution of HMDs in an effort to increase the rate of information transfer between the system and the human operator. For all the improvements in the resolution of an HMD, these solutions simply recommend rendering relatively simple graphics with more and more pixels rather than increasing the information density on the display, as is intended from the investment in higher resolution HMDs. A high-resolution display is of little use if it cannot be used to its full capacity and the compensation technique of rendering information on these displays with larger text and graphics limits the amount of information that can be displayed to the operator within the HMD.

2.5.2 *Image Stabilization: Initial Attempts*

Another form of compensation involves image stabilization that attempts to counteract the motion of the HMD. Wells and Griffin first attempted to perform image stabilization through a series of studies. They devised a system to measure the rotational motion of the head by configuring two pairs of helmet-mounted accelerometers to

measure pitch axis rotations and yaw axis rotations, respectively. The acceleration signals were filtered by double-integration to displacement, amplified and connected to the HMD electronics to adjust the image accordingly (Wells and Griffin, 1984). The 1984 study found success within the laboratory setting, while the 1987 study applied the same equipment to live flight-testing. They found that reading errors decreased from 16-23% to 3-5% with stabilization (Wells and Griffin, 1987). However, subjects could not make large amplitude head movements because of the use of high-pass filters in the algorithm. Low-frequency head movements resulted in large, unwanted image motions as well as inaccurate shifting of images on the display. Though there were certainly errors and inaccuracies, they were able to demonstrate that image stabilization was possible and effective, although this initial attempt left significant room for improvement.

2.5.2 Adaptive Filtering

Another method is to use adaptive noise cancellation to create a compensation input for an HMD. This type of compensation takes into account the reference of a primary signal, often from an aircraft mounted accelerometer which measures vibration levels, and then filters it through a biodynamic transfer function, which estimates the seat to head vibration transmission based on the aircraft type and flight regime. This filtered signal then moves information on the HMD synchronously with the sensed aircraft vibration to provide image stabilization for viewing tasks. This type of low-pass filtering allows the low-frequency voluntary head movements to pass through, while dampening the unwanted effects of higher vibrations. The Widrow Least Mean Squares (LMS) Algorithm and Instrumental Variable Approximate Likelihood (IVAML) method are

examples of applications of this method (Lifshitz and Merhav, 1991; Velger, 1998). However, the use of this method is subject to inaccuracies and delays. The reliance on estimations in the transfer functions is inaccurate, especially in the 4-6 Hz range as the motion of the head is augmented above that of the aircraft due to whole body resonance. These techniques are also vulnerable to non-additive interference, the effects of which are uncorrelated, or not caused directly by vibration but increase with vibration intensity. Examples are head displacement even after vibration is over or voluntary head movements. Finally, this technique can also be applied to signals from head-mounted accelerometers to determine movement of the head to integrate head position into the equation. However, in this application head trackers are required to have a high sampling rate (minimum 120 Hz, 240+Hz recommended). These high rate head trackers are expensive, not-readily available, and still do not completely solve the latency errors (Daetz, 2000). There have certainly been improvements shown by utilizing adaptive filtering techniques, but they still suffer from inaccuracy and latency issues and have not been tested outside of the computer simulation regime.

2.5.3 Conventional Filtering

An F-15 pilot, due to the aircraft's "hard wing" configuration, is subject to severe vibration, in certain flight regimes when the aircraft is buffeting. This low-frequency vibration can cause aiming errors of several degrees when tracking a target with an HMD, therefore the need for image stabilization. Studies found that, in addition to the prominent vertical vibration around 8.5 Hz associated with the buffeting, helmet motion was also affected by even lower frequency components suspected to be caused by

voluntary head motions (Smith, 2002). Therefore, adaptive filtering could not filter out this noise. The implementation of a conventional notch/lag filter was applied in a laboratory setting as well as in flight-testing on an F-15 (Daetz, 2000). A conventional filter was chosen because of the ability to filter out any remnant noise as well as not being reliant on an estimated relationship but focused on one output of interest, in this case that output being head rotation. The algorithm achieved a significant reduction in target acquisition time of 30%, while also minimizing both aiming errors and any noticeable latency to the pilots (Daetz, 2000). However, it was clearly distinguished between a tracking task (the objective of targeting with an HMD) and a viewing task (reading information/symbology on an HMD) and the conclusion was that a conventional algorithm was applicable to a tracking task and adaptive filtering was more appropriate for viewing tasks.

2.5.4 The VOR and Vibration Compensation

As discussed, the primary reason for the degradation in visual performance of HMDs is the VOR effect caused by certain wavelengths of low frequency vibration. Though the VOR may be understood from a fundamental standpoint, this research will delve deeper into this topic. The adaptive compensation techniques can require multiple signal inputs contributing to the latency and inaccuracy. To eliminate such issues, the goal is to create an algorithm solely based on measuring and predicting the movement of the eye. This requires a more in-depth understanding of the VOR that to date has not been achieved in the real-world application of HMDs. VOR research and analysis has mainly been conducted in the medical field with a focus on determining patient vestibular

deficiencies. Two such studies were conducted by applying a helmet apparatus to perturb the subject's head in the low-frequency domain (0-10 Hz) and using EOG to measure the VOR effect. One study analyzed this VOR effect based on fixation of a stationary target, while later research incorporated a head-free tracking of a moving visual target. Both studies found that the VOR was predictable and acted linearly up to approximately 4 Hz, however; they found that the dynamics of the VOR began to vary at greater than 4 Hz (Tabak, et al., 1997; Tangorra, et al., 2004). The Tabak study, which involved simple fixation on a target, found that VOR gain *decreased* up to 8 Hz, where it then began to increase again. The Tangorra study, which had the subject's tracking a moving target, found the VOR gain to *increase* at frequencies greater than 4 Hz. Both studies concluded that the VOR has non-linear dynamics at higher frequencies, but suggested the need for further evaluation in this domain. The results of this present experiment will validate these earlier findings and provide a foundation in which to further research on future compensation algorithms.

2.6 Conclusion

The long term, overall goal of this research is to determine how the image of a HMD can be stabilized with respect to the human eye to improve human performance. As previously discussed, many compensation techniques have been studied and some have been applied successfully within a simulation environment. However, while it is understood that the VOR has a destructive effect on visual performance in certain vibrating environments, little to no research has been completed to study and characterize

this effect outside of a medical environment. The focus of this study is on establishing a baseline of eye motion relative to head motion, specifically by isolating and analyzing the VOR effect. This will be accomplished by simplifying the effects of real-world vibration environments by focusing on low-frequency, sinusoidal vibration in only one direction (z-axis), while introducing low-level, simple viewing, reading and tracking tasks. With an established baseline, further research can be performed to determine whether the VOR can be successfully measured and characterized to be used as the primary input into a vibration compensation algorithm in more complex, multi-axis real-world vibration environments. Finally, the data that is collected will be used to attempt to form initial predictive algorithms of eye position based upon eye movement data that directly measure and react to the VOR to provide image compensation in HMDs. The feasibility and predictability of these algorithms will ultimately be explored in more complex, multi-axis operational environments.

Chapter 3 – Method

3.1 Chapter Overview

This chapter outlines the development of the hardware to support this research as well as the experimental method developed and executed to answer the research questions proposed in Chapter 1. As previously discussed, this area of research, which seeks to understand the nature of the Vestibulo-Ocular Reflex in a vibration environment, determine its effect on human performance while using Helmet Mounted Display's, and counteract its detrimental characteristics, has not been thoroughly investigated. This project sought to establish a baseline for further investigation. The general method employed was to first develop an apparatus for synchronously recording the movement of the user's head and their eyes while viewing an HMD and then to design and conduct a study in which the human subjects are exposed to low amplitude, low frequency vibration while wearing the apparatus to assess its utility in this endeavor.

3.2 Apparatus Development

3.2.1 Requirements

The various uses of HMDs have greatly increased as technology has improved as the functionality of these displays has increased while size and weight have decreased. The primary use of HMDs in the Air Force and DOD as a whole are those utilized by pilots of both fixed-wing aircraft and helicopters. However, research continues to demonstrate the potential utility of these displays to other vehicle operators and dismounted infantry. The systems may differ greatly among various combat platforms, whether it is the fully helmet-integrated HMD in the F-35 or simple monocular displays

still used by many helicopters, but the objective remains the same for both: provide continuous, critical information to the operator to improve situational awareness and performance. Therefore, the goal of this research was to simulate equipment being utilized by military pilots, the primary users of HMDs.

This included using a helmet, representative of a typical flight helmet, and modifying this helmet to attach a programmable imaging system, representative of a simple HMD. The display was to be as light as possible because the focus of the study was on eye movement. Eliminating other variables, such as neck strain and possible large head displacements caused by a heavy displays with a forward center of gravity, made isolating eye movement easier. However, the display needed to be able to represent operational displays and to provide a reasonable quality image. Additionally, the helmet-display system had to be modified to provide the ability to track and record this behavior of the subject's eyes.

The Human Performance Wing at the Air Force Research Labs, and specifically the Battlefield Awareness (BATMAN) office, was consulted on equipment design and production. Their expertise on providing airmen technologically advanced, performance-enhancing equipment in the battlefield proved invaluable to this research.

3.2.2 *Helmet*

A GENTEX HGU/53 Aircrew Helmet was selected and modified for use in this experiment. Pilots of numerous aircraft, both rotary and fixed wing, use the HGU/53 and its variants. Figure 1 shows an image of the helmet. The modified helmet included a hard protective helmet with external mounts for attachment of a visor and a cushioned inner surface with padding that can be modified to provide an enhanced fit to each user. The

helmet also included a chinstrap, which helped to stabilize the helmet on the user's head. This helmet was then outfitted with a visor for three different reasons. First, the visor served as a stabilizing base for additional equipment, as it was easier to modify the visor than the helmet. Second the visor could be easily removed and attached to a different helmet depending on head size. Finally, the visor provided glare protection and reduced the effect of ambient lighting during testing.



Figure 1. Standard Flight Helmet with No Modifications

The visor was then modified to provide an imaging and optical eye-tracking platform. These modifications included the addition of a binocular Liquid Crystal (LCD) display, which was mounted to be viewed by the subject as they looked forward normally. Next, a bracket was created to mount an Infrared (IR) sensitive camera to track the eye and an IR Light Emitting Diode (LED) light source to illuminate the eye. However, the visor was found to interfere with the eye tracker as the resulting image was blurred and a sharp spectral reflection from the LED was not present. A hole was drilled

into the helmet visor at the location to the right of the right eye to eliminate any reflection or absorption of the IR light as it passed through the visor. The LED and the camera were re-mounted on a bracket behind the hole in the visor and positioned to capture the image of the eye and provide a reasonable image for video-based eye tracking.

Finally, the helmet was modified for cable and wire maintenance. A Velcro strip was placed across the top to secure the various cables from the display, camera and LED during the experimental sessions. Additionally, hooks were attached to both sides of the helmet to secure the wires from the EOG electrodes during the test sessions. Figures 2 and 3 show the finished helmet apparatus from two different angles and clearly illustrate the various equipment mounted to the helmet.

3.2.3 *Display*

The binocular display was modified from a pair of Vuzix Wrap 920 augmented reality glasses. The display includes a pair of full-color VGA LCDs with magnifying optics to position the image to optical infinity and provide an image having a diagonal viewing angle of 30 degrees. The screen was connected to a laptop computer via a standard VGA cable and powered by the laptop via a USB cable. The only modification to the display was to remove it from the original glasses, and to add 20 foot VGA and USB cables to connect the laptop during the test sessions. The extension cables permitted the laptop to be off of the vibration table on which the participant was seated.

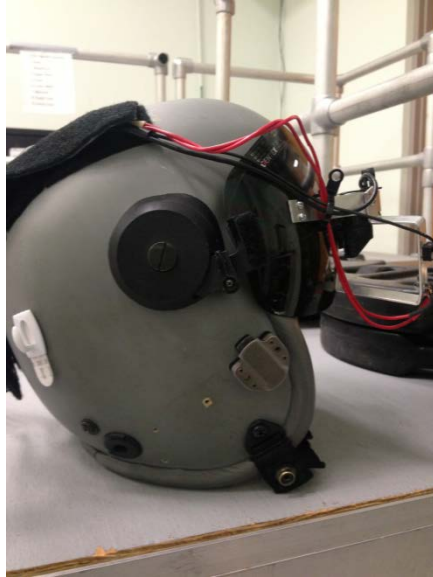


Figure 2. Modified Flight Helmet: Side Profile

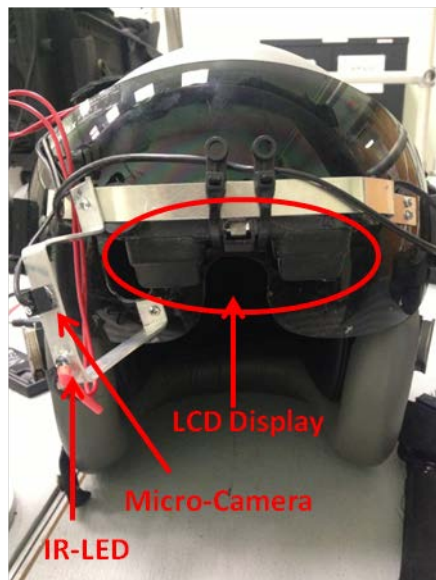


Figure 3. Modified Flight Helmet: Front Profile

The projected images on the display and thus viewed by the subject were generated by the laptop. All of the tasks and calibration targets were generated with PowerPoint, which is detailed more extensively in later sections. The final adjustment was adding a black strip to the right side of the images projected on the screen to eliminate glare from the hole, which was created in the visor to support the optical eye tracking apparatus. HMDs are both monocular and binocular depending on how the display is being utilized and what the mission calls for, but there is no research to suggest that there are differences in how vibration degrades their performance. Given the increased development and implementation of binocular HMDs, such as the system used in the F-35, a binocular display was selected for use in this study. The display was mounted as previously described and can be seen in a close up in Figure 4.

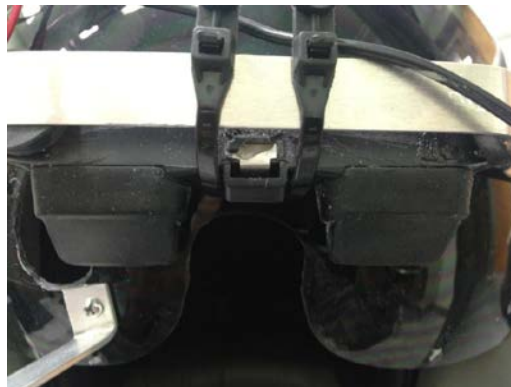


Figure 4. Binocular LCD Display

3.2.4 Video-Based Eye Tracker

As the goal of the research was to better understand the behavior and characteristics of the eye under vibration conditions, specifically the effects of the VOR when using an HMD, one method of tracking and analyzing these movements was through the application of video-based eye tracking. Commercial eye trackers were not

available to meet the needs of this study, both due to expense and more importantly, our inability to modify and use these trackers in conjunction with HMD viewing. Therefore an open-source path was taken to build and utilize a lightweight, customizable eye tracker (Babcock and Pelz, 2004). This eye tracker includes a very lightweight camera, fit with an infrared filter and a directional infrared light source to provide illumination of the pupil.

To track the eye in video based recording, the eye needed to be illuminated in the IR spectrum so that directed light from the light source would not produce visible glare. Installing an IR LED off-axis with respect to the camera's focal axis would result in a dark-pupil illumination and a corneal reflection as seen in Figure 5. Using the dark-pupil method, the centroid of the pupil and the reflection could be tracked. These two points could then be used to determine gaze by calculating the vector between the centers of both the two landmarks.

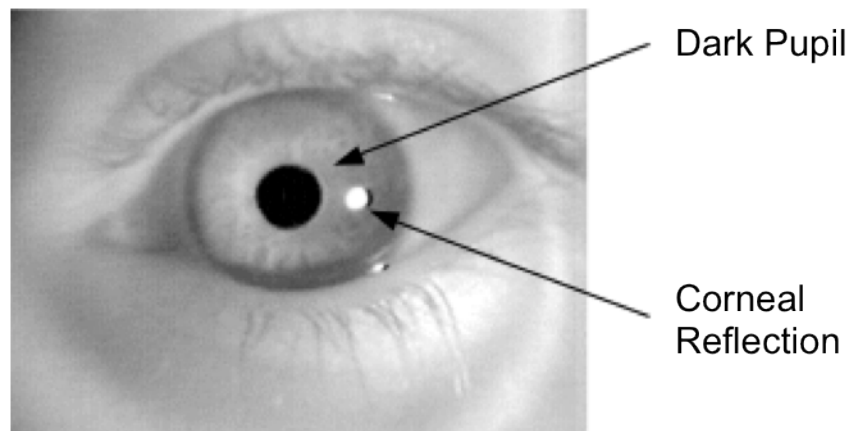


Figure 5. Example of Dark-Pupil Illumination with Corneal Reflection

Based on the published standards for eye safety, an irradiance level less than 10 mW/cm² is considered safe for constant IR exposure in the 720-1400 nm range (ICNIRP,

1997, 2000) as seen in Figure 6. The 5mm Everlight Infrared LED light source was driven with custom electronics, seen in Figure 7, which limited the maximum flow of current to the LED and provided flexibility to adjust the current to the LED during system setup. The IR LED being used had a peak wavelength of 980 nm. A 12V DC input was used to drive the LED and a 1K potentiometer was used to regulate the voltage levels. This potentiometer was used to adjust the illumination of the eye with the lowest possible power while obtaining a good quality image. A 100-ohm resistor in the circuit maintained a current less than 80 mA to the LED, providing illumination well within safe limits. This peak current was independently measured using a pair of independently calibrated current meters to verify this peak current.

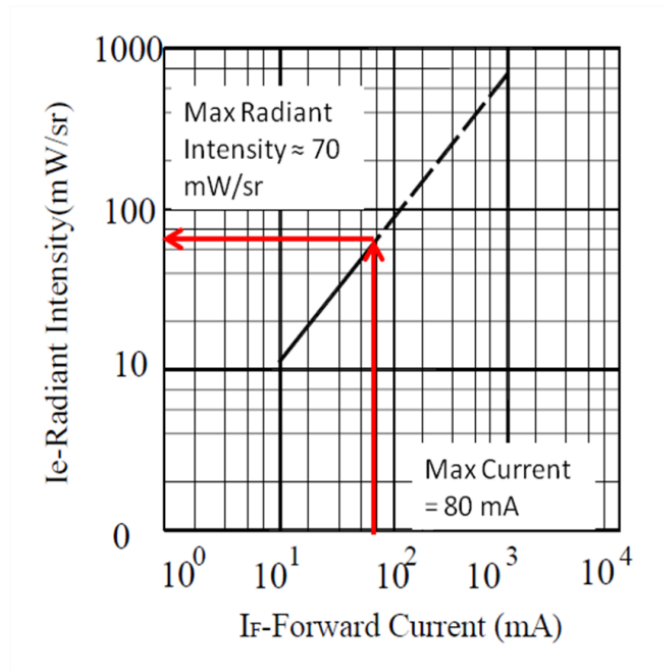


Figure 6. Relative Intensity vs. Forward Current for Everlight 5mm Infrared LED

According to Figure 6, at this maximum output value, the radiant intensity was approximately 70 mW/sr. This value was confirmed through measurements with a

thermocouple. Given that the LED was positioned no closer than 6 cm from any subject's eye, the corresponding irradiance at this distance was 1.94 mW/cm^2 . This max irradiance provided by the system was therefore significantly lower than the recommended safety levels and the required illumination for this study did not approach the maximum recommended irradiance level.

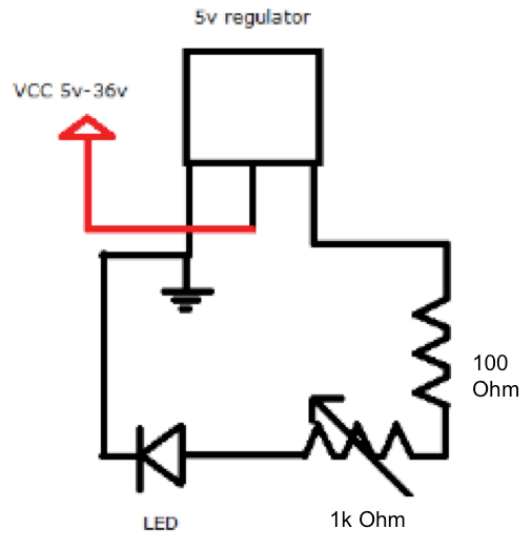


Figure 7. IR LED Circuit

A SuperCircuits micro-lens video camera was used to monitor the movements of the eye and was positioned to be pointed directly at the eye. The dimensions of the chosen micro-camera were $.375 \text{ in}^2 \times .675 \text{ in}$. The small size of the camera was ideal to minimize weight and to allow flexibility in apparatus design. Even with the small size, the camera provided sufficient image quality for analysis with 420 TV lines. The camera was positioned 1 inch away from the slightly off-axis light source. This positioning is illustrated in Figure 8.



Figure 8. Camera and LED Bracket and Position

The camera utilizes a .25 in CMOS imager sensor, which is sensitive to both the visible and infrared light spectrum. In order to isolate the IR spectrum from ambient lighting for eye tracking with the dark-pupil method the camera was fit with an IR filter. To achieve this purpose a visibly opaque #87 Kodak Wratten 2 Optical Filter was used. A standard hole punch was used to create an appropriately-sized filter to fit within the lens barrel of the camera, allowing the filter to be placed adjacent to the sensor. The camera was connected to a DVR, which recorded the movement of the eye throughout the test session and was powered with 12 V and 20 milliamps. The camera's small, compact size can be seen in Figure 9.

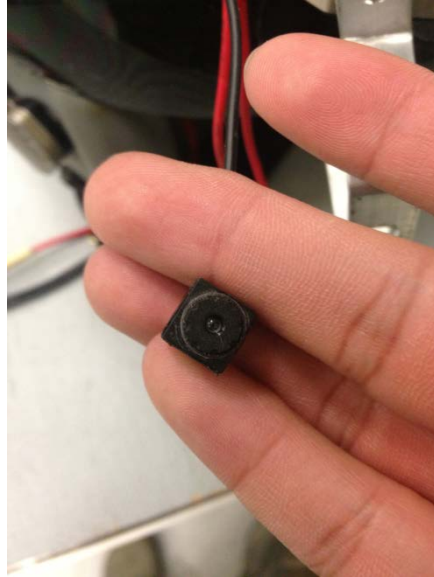


Figure 9. SuperCircuits Micro-lens Camera with IR Filter

3.2.5 *Electro-Oculography (EOG)*

The few studies that have specifically investigated the VOR have used electro-oculography (EOG) to track the movement of the eyes with respect to the head. This procedure records the potential difference (in mV) between the two electrodes as the eye moves from the center, neutral position towards either of the electrodes. An estimation of the conversion from mV to degrees was derived from the calibration data resulting in approximately .04 mV/degree. Research has found this relation to be linear in visual angles up to 30° (Young and Sheena, 1988). Therefore, it was decided that in addition to the video eye tracker, we would employ EOG to gain eye movement data. The combination of two eye tracking methods also reduced the risk as the effect of vibration on the video eye tracker and our ability to analyze the video images was uncertain.

During the experiment, the subjects wore electrodes on both temples and their forehead, as well as an electrode both above and below the right eye. The data was

collected on two separate channels; one indicating horizontal and one indicating vertical eye movements. These electrodes were attached to a BIOPAC system. The horizontal data was collected from the electrodes mounted on the right and left temples, with a ground on the forehead. The vertical data was collected from the electrodes attached above and below the right eye, with a ground on the forehead. Figure 10 shows the general EOG electrode placements. Ideally, both the optical eye tracker and EOG would provide comparable data. However, due to vibration of the head, it was possible that the optical eye tracker would move somewhat with respect to the head while the EOG would still track eye movements with respect to the user's head. The EOG instrument is a research instrument that has been certified for conformity according to the applicable EN standards.

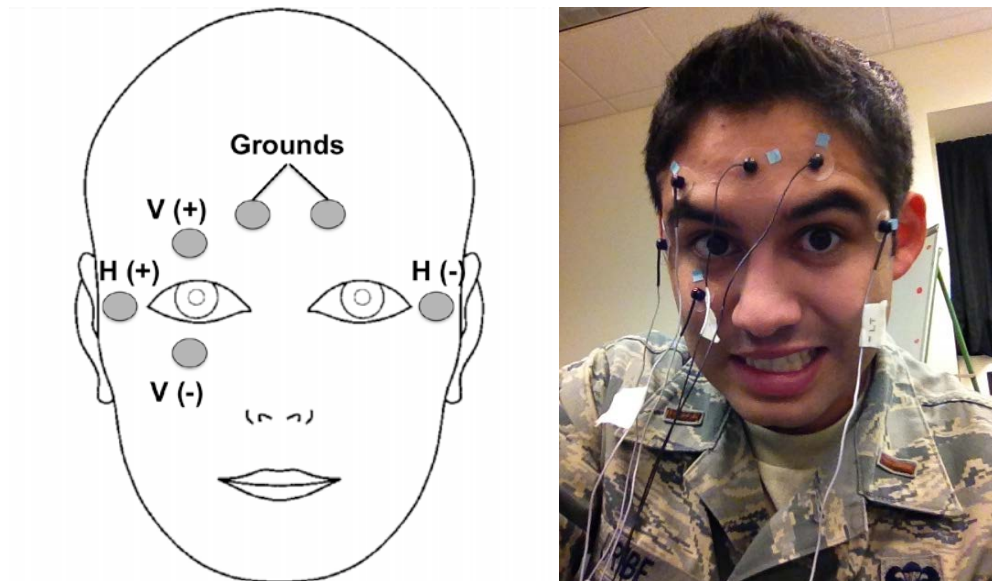


Figure 10. EOG Electrode Placement

3.2.6 Accelerometer/Bitebar

A bite-bar was used to measure head accelerations. The bite bar consisted of a custom fitted mouthpiece for each subject, with an attachment for an accelerometer. A 5g tri-axial BIOPAC accelerometer was attached to the bite-bar for measuring vibration of the head along the three axes, although the primary focus was on the z-axis. Figure 11 displays the mouth guard and accelerometer attachment, while Figure 12 is an image of the tri-axial accelerometer. The accelerometer was calibrated before each test session and connected to the BIOPAC system. The acceleration data was collected concurrently with the electro-oculography recordings.



Figure 11. Custom Mouthguard with Accelerometer Mount



Figure 12. Tri-axial Accelerometer

3.3 BIOPAC/Acqknowledge

The BIOPAC system is the device used to collect the EOG and accelerometer data. It was connected to a PC loaded with the corresponding Acqknowledge software via an Ethernet cable. The Acqknowledge software simultaneously records the data collected by the BIOPAC on five separate channels when prompted by the investigator. Table 1 lists the five channels and the data collected on those channels. The data was then exported from the software in .xlsx and .txt format for analysis.

Table 1. BIOPAC/Acknowledge Channels

Channel	Data	Sampling Rate [Hz]
1	Horizontal Eye Movement	1000
2	Vertical Eye Movement	1000
3	Accelerometer: X- axis	250
4	Accelerometer: Y- axis	250
5	Accelerometer: Z- axis	250

3.4 Participants

Six volunteers participated in the experiment. The ages of the participants ranged from 22-26 years old, with a mean age of 23. The participants included 3 males and 3 females. Each of the participants had to meet certain qualifications, outlined in an initial screening questionnaire. Participants were not to have experienced any vestibular

anomalies (including inner ear infections) within the month preceding the investigation. Participants were not to have experienced any discomfort or pain symptoms associated with the musculoskeletal system, particularly in the spine and neck. Additionally, female participants could not be pregnant and could not have had breast implants. Participants with corrective vision through LASIK, PRK or soft contacts were qualified but individuals requiring glasses or hard contacts were precluded from participating in the experiment as these lenses were expected to interfere with the image-based eye tracker.

3.5 Facility

The study was conducted in the Single-Axis Servohydraulic Vibration Facility supported by the Air Force Research Laboratory's 711th Human Performance Wing. The human-rated Single-Axis vibration table is capable of recreating operational exposures in the vertical or Z direction. A rigid seat with seat pan and seat back cushions was mounted on top of the Single-Axis platform. The table floor and seat base were instrumented with a tri-axial accelerometer pack consisting of three miniature accelerometers (ENTRAN EGA 125-10D) embedded in a Delrin cylinder. Tri-axial accelerometer pads were placed between the subject and seat pan cushion as well as the seat back cushion. The pads consisted of a rubber disk with a tri-axial accelerometer mounted in the center. The pads measured the accelerations entering the human body at the points of contact with the seating system. Instrumentation of this equipment occurred in the initial setup of the study to ensure that the targeted acceleration levels were being generated and transmitted to each of the participants.

Figure 13 shows the test session in progress from the view behind the investigator and technician stations and is marked to show the equipment used during this experiment.

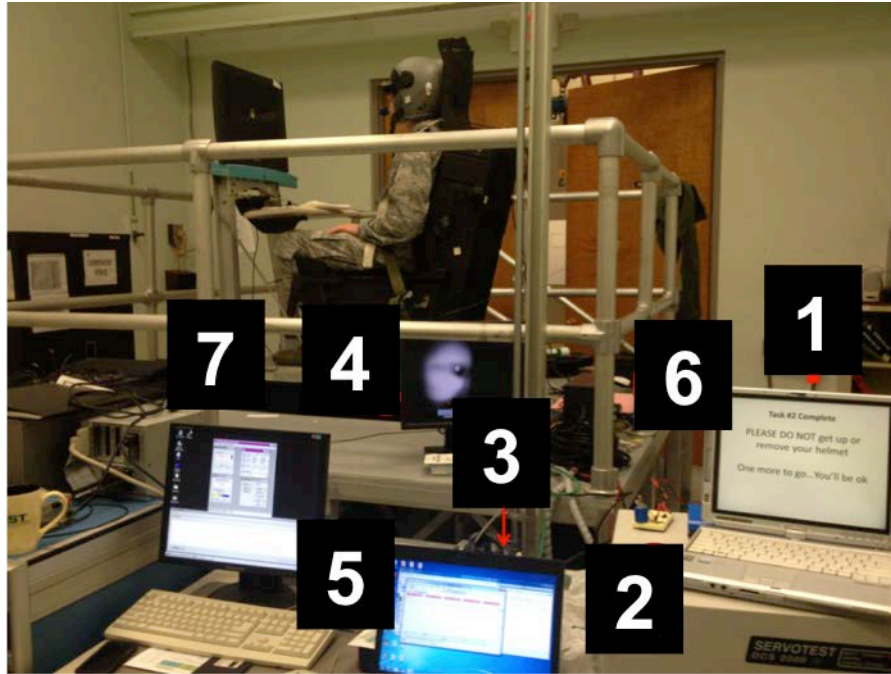


Figure 13. Single-Axis Servohydraulic Facility with Test Equipment

The investigator and technician were seated off of the main vibration table at a table with the equipment needed for the test session and data collection. The laptop loaded with the tasks for the test sessions was positioned off to the side of the table with the screen facing the investigator and technician (1). Since the test session was automated, the laptop did not need to be manipulated during the session, but it allowed the investigator and technician to monitor the progress of the experiment. Next to the laptop was the LED driver and dial, which allowed the LED brightness to be adjusted to provide the best image in the video eye-tracking recording (2). In front of the investigator was the DVR being used to collect the eye tracking video (3). Behind the DVR was a

computer monitor displaying the data being captured by the helmet-mounted camera, giving a real-time look at the subject's eye (4). Directly in front of the investigator was the laptop (5) connected to the BIOPAC system (6). This laptop ran the Acqknowledge software and was constantly in use by the investigator throughout the experiment. Seated next to the investigator was the facility technician who ran the vibration table, inputting the necessary information to vibrate the platform at the desired frequency according to the test sequence (7).

3.6. Vibration Exposure

The participants were exposed to a low frequency, sinusoidal vibration signal ranging between 0 and 10 Hz at .1 g peak ($\sim 0.69 \text{ ms}^{-2}$ rms). The signal was generated at 1024 samples per second and continuously repeated, as necessary, to meet the exposure requirements for each test session described below.

3.6.1 Subject Safety and Risk

The low levels of vibration and brief exposures used in this study are associated with a low potential for health risk in accordance with the current human exposure guidelines (ISO 2631-1: 1997). Figure 14 shows the weighted acceleration values for each frequency component compared to the Health Guidance Caution Zones provided as guidelines in ISO 2631-1: 1997. As shown in the figure, even for the worse case exposures lasting 10 minutes, there is very low potential for health risk.

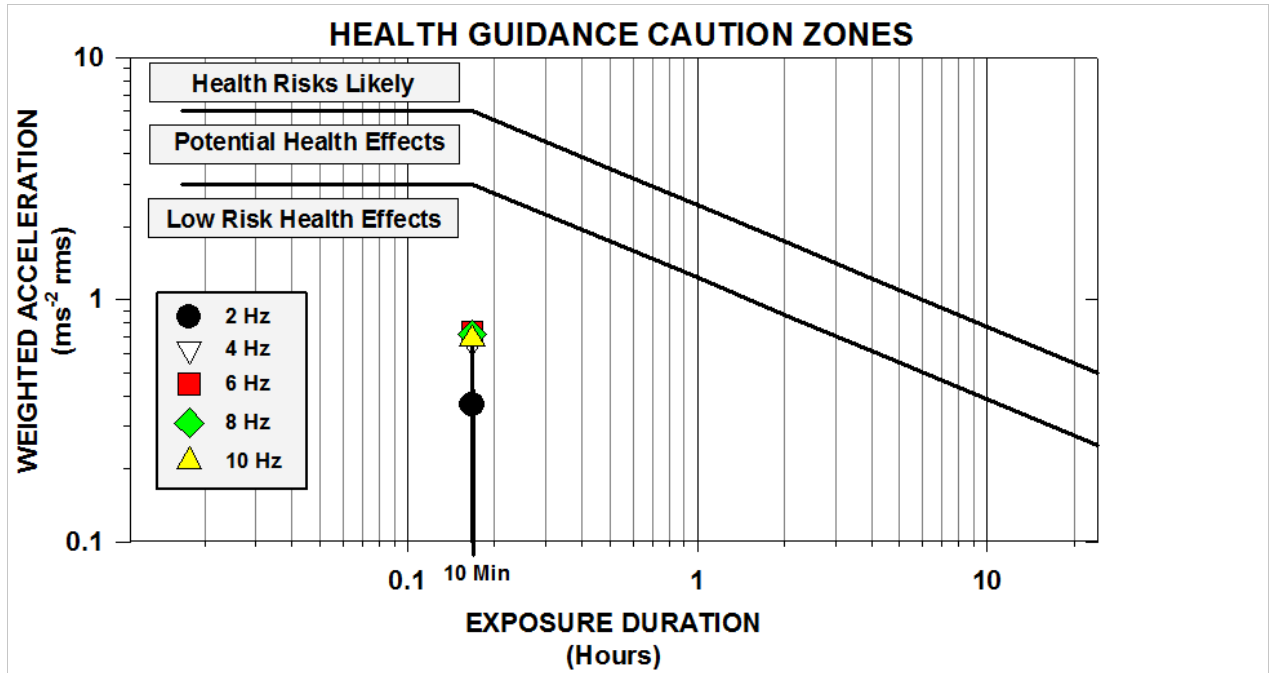


Figure 14. Health Guidance Caution Zones (ISO 2631-1: 1997)

The level of vibration is akin to the vibration a participant would encounter in an everyday, real-world scenario, such as traveling in a car over a rough or unpaved road, or when encountering brief, minor turbulence in a commercial aircraft. There is no risk of hearing damage or loss. The use of a helmet provides some hearing protection, although noise levels in the facility are quite low at the targeted low frequencies. Health guidelines indicated that the participant might experience fatigue, similar to what might be expected during mild exercise as a result of the vibration exposure. Some fatigue may be the result of the performance tasks. It was anticipated that most of any discomfort will disappear once the testing is completed and all equipment is removed.

3.7 Experimental Tasks

To investigate the VOR from a performance viewpoint, the subject needed to utilize the HMD as a pilot would in a real-world scenario. To establish a baseline, simple viewing and tracking tasks were created for the participant to accomplish while visually interacting with the HMD. Though the specific tasks were not meant to mimic the types of tasks an operator would encounter in a real-world scenario and interaction with an HMD, they were created to be representative of types of low-level visual tasks that the operator would perform while using an HMD and to capture the different types of eye movements associated with the performance of visual tasks.

The tasks were created in Microsoft PowerPoint, displayed on the VGA display, and viewed by the participant. PowerPoint was used because it provided the stimuli necessary for motivating the simple visual tasks and provided a reliable timing mechanism for progressing through the various images. The development of more complex visual stimuli to motivate more complex visual tasks would likely require more extensive video programming software.

Each task was programmed to be 15 seconds in length with a 20 second acclimation period between each task. PowerPoint also provided the ability to create the tasks and automate them for the entire test session. Once the investigator began the session, the program ran automatically at exactly the same time intervals for each subject. Since each subject saw the exact same stimuli at the equivalent moments in time, analysis of specific intervals of time among subjects or test sessions was simplified.

3.7.1 Performance Task A (Single Target Fixation)

A single crosshair image was projected to the user via the LCD screen mounted on the helmet. The crosshair remained in the center of the screen, as seen in Figure 15, and did not move throughout the duration of this task. The subject attempted to fixate on this point for the entire duration of the task. This simulates locking on to a target or interpreting a single, stationary point of data or text.

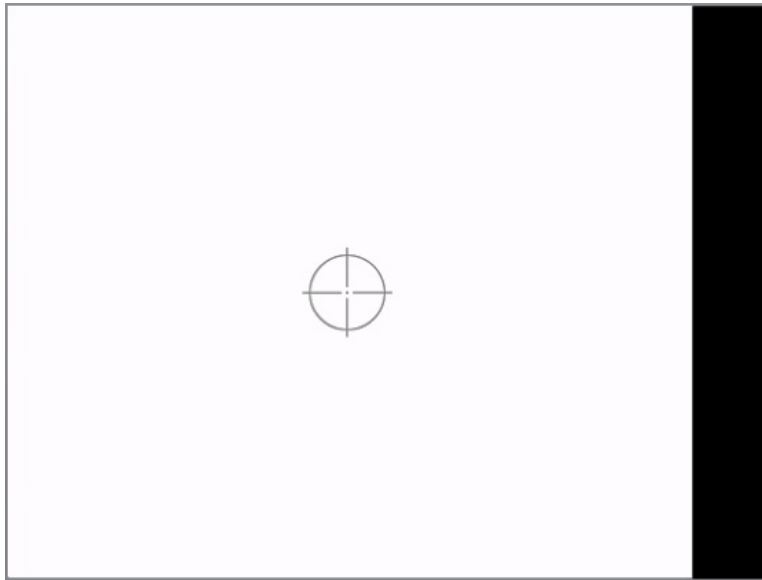


Figure 15. Example Screen: Task A-Single-Point Fixation

3.7.2 Performance Task B (Smooth Moving Target)

A single crosshair image was projected to the user via the LCD screen mounted on the helmet. In this task, the crosshair began on a point on the screen and then moved around the screen in a smooth motion always remaining visible. The various velocity and acceleration components depended on the motion paths. For the longer paths, the maximum velocity was 181 pixels/s for 2.08 seconds, while the shorter paths had a max

velocity of 189 pixels/s for .8 seconds. The target reached a velocity of 0 m/s at the apex of each of the turns while decelerating and then accelerating again between .76-157 pixels/s depending on the target path. Figure 16 shows the path of the target as it moved across the screen; the arrows reflect the path of motion. The subject was to lock on to the target and follow it throughout the duration of the task run. This simulates the subject tracking a moving target.

Early versions of this task maintained a constant target velocity. However, it was clear that as the target changed direction on the screen, the participants were unable to maintain track of the target. Therefore, the task was modified such that as the target approached a turn it slowed before beginning motion along an alternate vector. This motion path allows for analysis of eye movement during object tracking.

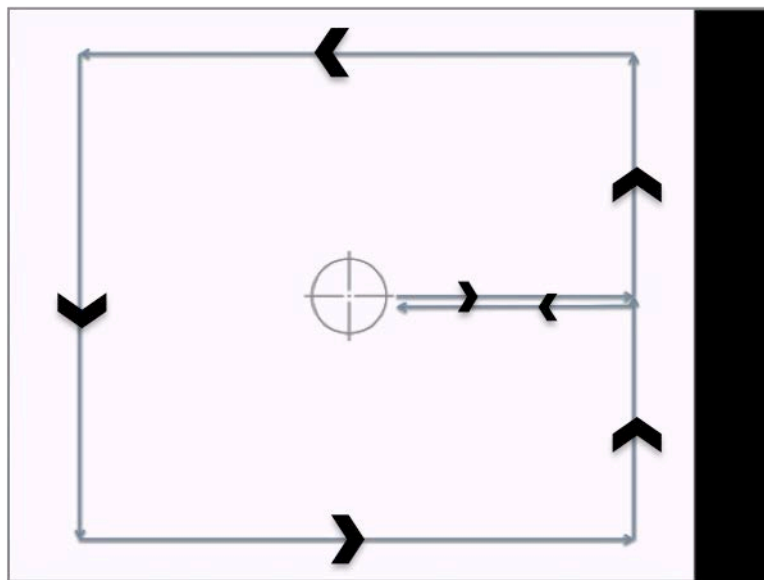


Figure 16. Example Screen: Task B- Smooth Pursuit Path

3.7.3 Performance Task C (Eye Movement)

During this task, a single crosshair image was projected to the user via the LCD screen mounted on the helmet. In this task, the single crosshair began at a point on the screen and then disappeared and reappeared in one of 8 different locations based upon the 3x3 grid, which is seen in Figure 17. The user was to acquire and lock on to the target. The target continued to change locations throughout the duration of the task run each second. This simulates the user fixating on various objects and then quickly moving from one point of data to another in a different location rapidly. The aim of this task was to understand the effect of vibration on the saccadic movement of the eye. Note that this is not a search task as the target was large enough to permit its location to be easily determined in peripheral vision and the target appeared in a fixed sequence.

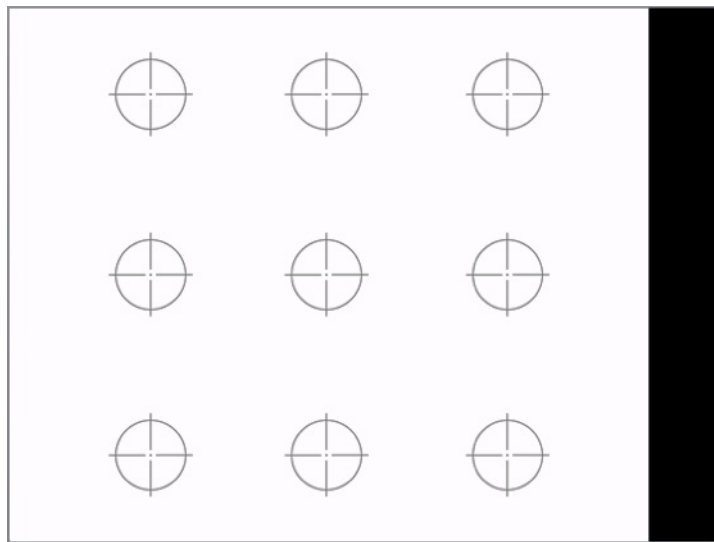


Figure 17. Example Screen: Task C- Eye Movement

3.8 Test Sessions and Testing Sequence

3.8.1 *Experimentation Overview*

The six subjects were required to complete two separate test sessions on two different days. The same setup and procedure was followed for both of the sessions, with the difference being the order the tasks were accomplished and the frequency exposure order. Within the two test sessions, all factors remained constant for each of the six subjects. The details for the experiments are outlined in Appendix E and F. Appendix E is the sequence time sheet, showing the exact time segments for every part of the tasks. Appendix F is an outline of the test procedure from setup to the exporting of data.

3.8.2 *Setup*

The experiment did not include a formal training session. The tasks were explained to the participant prior to each experimental session. Prior to initiating the test session, the participant read and answered a pre-experiment questionnaire to determine vestibular health for both present time and past history. This screening checklist can be found in Appendix A. Next, the custom mouth guard was fit for each individual subject. The accelerometer was calibrated and then attached to the mouth guard. The subject was then seated and harnessed into the flight seat. The EOG electrodes were then attached in the six positions on the subject's head using electrode gel and secured with medical tape. After verifying that the Acknowledge software was recording the vertical and horizontal eye oscillations, the helmet was positioned on to the head of the participant. The visor was lowered and adjusted until the participant verified that they could clearly see the 3 x 3 grid on the display and the investigator verified that the eye could be clearly recorded

by the camera. Finally, the bitebar with the mounted accelerometer was inserted into the participant's mouth. Figure 18 shows a participant in the ready state for test initiation. The test session was then initiated and the investigator began the recording of the DVR and started the test session simultaneously. The video eye-tracking data was collected continuously over the duration of the test session and terminated manually once the test session was completed. The start time of the recording was annotated by the investigator and inputted into a table, which then gave the specific time intervals for each task and frequency.

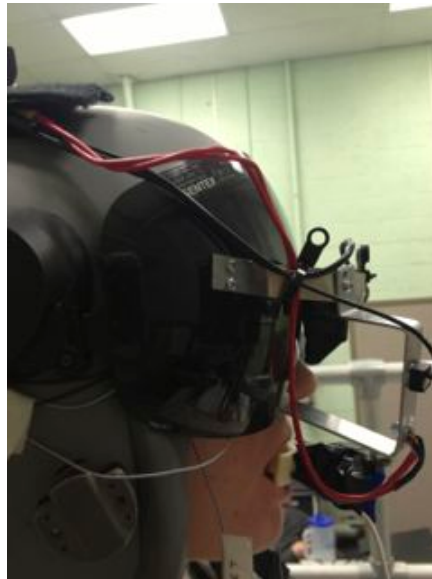


Figure 18. Subject in Session Ready State

3.8.3 Test Session

As soon as the investigator initiated the test session, the participants were shown instructions for the Calibration task on the HMD screen. During this task, the participant was asked to follow and fixate on the crosshair at five different locations on the screen, one at a time, as seen in Figure 19. This calibration occurred under no vibration.

As discussed previously, the order of the tasks differed between the two sessions. The following sequence is for Session 1. Once calibration was established, the subject began Task A. The first test vibration frequency was no vibration at 0 Hz. The first 20 seconds of the task was the acclimation period in which instructions were projected to the subject via the HMD screen. The subject then performed Task A for 15 seconds.

As soon as the actual task began following the 20 second acclimation period, the investigator dropped a flag in to the data via the Acqknowledge software and collected for the remaining 15 seconds of exposure at the given vibration frequency (0 Hz). The flag was used to isolate the 15 seconds of task duration in later analysis. The vibration frequency increased to 2 Hz and the subject was then exposed to this specific frequency for 20 seconds without having to perform the task.

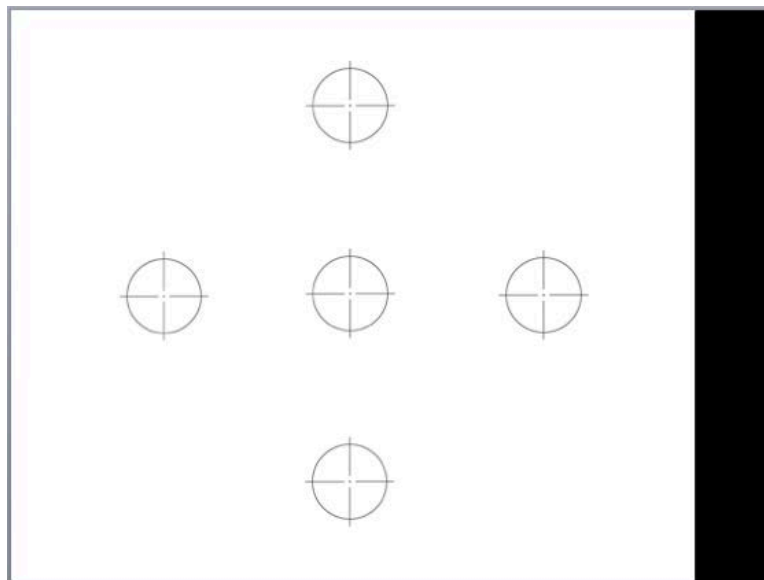


Figure 19. Calibration Screen

These 20 seconds allowed the vibration table to reach full magnitude for the selected frequency, for the investigator to begin another recording at the selected frequency, and for the participant to become acclimated to the frequency. Data collection was triggered as soon as a new recording was opened by the investigator, which occurred after saving the data at the end of each of the individual frequency tasks. After this 20 seconds, the subject performed Task A for 15 seconds. The vibration then increased incrementally to 4 Hz and again a 20 second acclimation period ensued before the participant performed the task for 15 seconds. This same procedure of increasing the frequency incrementally and allowing 20 seconds of acclimation exposure before 15 seconds of task performance occurred at 0, 2, 4, 6, 8 and 10 Hz. After the first task was finished the participant received a 2:15 minute break while remaining seated and strapped in while the data was uploaded and saved. Then Task B began again at 0 Hz and increased to 10 Hz incrementally at 2 Hz, with the same 20 second acclimation period.

This same procedure, with the break in between each task, occurred for each of the 3 tasks for Experimental Sessions 1 and 2. After the subject completed the 3rd task, the subject performed a post-experiment questionnaire, which can be found in Appendix B. In Experimental Session 2, the procedure was exactly the same, with the exception being that the task order was varied from A, B, C to C, A, B and the vibration change was not linear but also varied. It followed a 0, 8, 4, 2, 6, 10 Hz vibration sequence. Total subject exposure time to vibration for each task was 175 seconds (2.92 minutes) that equated to a total exposure time for each experimental session of 525 seconds (8.75 minutes). Table 2 lists the task order associated with the two experimental sessions while

Table 3 details frequency exposure order and the amount of exposure time. A 48-hr rest period was required between vibration test sessions.

Table 2. Experimental Task Order

Experimental Session 1	Experimental Session 2
<i>Calibration</i>	
Task A (3.5 min)	Task C (3.5 min)
<i>2:15 rest period</i>	
Task B (3.5 min)	Task A (3.5 min)
<i>2:15 rest period</i>	
Task C (3.5 min)	Task B (3.5 min)
<i>End Session</i>	

Table 3. Frequency Exposure Order

Experimental Session 1	Experimental Session 2
0 Hz	0 Hz
<i>20s acclimation period @ next Hz</i>	
2 Hz	8 Hz
<i>20s acclimation period @ next Hz</i>	
4 Hz	4 Hz
<i>20s acclimation period @ next Hz</i>	
6 Hz	2 Hz
<i>20s acclimation period @ next Hz</i>	
8 Hz	10 Hz
<i>20s acclimation period @ next Hz</i>	
10 Hz	6 Hz
<i>End Task</i>	

Notes:

Vibration Exposure Time per Task = 175s (2.92 min)

Total Vibration Exposure Time per Session = 525s (8.75 min)

Chapter 4 - Results and Discussion

4.1 Chapter Overview

As discussed previously, the long-term intent of this research was to establish research baselines in the areas of HMDs and vibration, specifically with respect to eye motion. The experimental portion of this work was to demonstrate the applicability and robustness of the apparatus, as well as to collect some initial data, which could be used for further development towards the long-term goal. To keep this task manageable, the participant pool was small (6), the three tasks were basic visual tasks which could be easily understood, and the duration of the tasks were short, even when considering that this data collection was repeated during two independent sessions. Therefore, the total data collection across all subjects, tasks, and sessions provided performance data for 290 seconds. However, given that several channels were sampled at 1000 Hz, the amount of data collected was still significant. Due to time limitations, the focus of the data analysis was scoped to provide an understanding of human performance during Task A, the single point fixation task, Task B, the fixation on a moving target, and the combination of the two tasks. These specific tasks were chosen for comparison because both tasks dealt with the participant's ability to fixate on a point, whether moving or stationary and the objective was to analyze the effects of vibration on these tasks.

Although several different types of data were collected for each subject, the analysis was further scoped to include only the head acceleration and eye response amplitudes collected through EOG by the BIOPAC system. These data included both horizontal and vertical eye movements sampled at 1000 Hz, and head acceleration from the tri-axial accelerometer mounted to the participant's bitebar sampled at 250 Hz in the

separate X, Y, and Z directions. All of the data collected by the BIOPAC system was gathered as soon as the investigator manually triggered the collection via the AcqKnowledge software as described in the previous section. While video of the eye was collected continuously throughout the duration of the test sessions these data were only applied to aid the interpretation of the EOG data and was not independently analyzed.

All of the participative data were documented and compiled for comparison and analysis and to aid in improvements for future studies.

4.2 Preparation of Data

Upon the completion of all participants testing, the collected data needed to be converted and prepared for analysis. The first step in preparation was determining which segment of the participant data was of importance within each signal file. The Acqknowledge software unfortunately only placed a flag in the data and did not have an option for segmenting data before or after the flag. Thus, this segmentation needed to be done manually. This required recording the flag times for each file, which designated when the participant started performing the task. Once these start times were recorded, the data were segmented based upon the duration of the stimulus presented during the experiment. As described in Chapter 3, the calibration task had a duration of 20 seconds, while Tasks A-C had durations of 15 seconds. Thus, the appropriate duration time was added to the start time to give a time segment of actual task data. The resulting time sheet for each participant, session, task and frequency are attached in Appendix C and provided the segment of importance for each data set. Finally, the signal files for the EOG and the accelerometer measurements were converted into Excel files and read into MATLAB for

processing. Each data file was named using the following naming convention:

SUBJECT-TEST SESSION-FREQUENCY-TASK. For example, the data set for Subject 3, in their 2nd test session, completing the tracking task (B) at 4 Hz would appear as: 3-2-4-B.

The eye video recordings were time synchronized with collection of the eye movement and accelerometer data. A time sheet was created for each participant and session using the recorded time and accounting for the appropriate time increments between tasks as defined in the stimulus presentation software. Appendix D contains the detailed time sheets, providing the exact time segments for the various tasks and/or frequencies. This time data is necessary to isolate specific tasks and/or frequencies for each participant.

4.3 Data Processing

Given the specific aims of the research, the data needed to be processed from raw form into data that could be used in the analysis. Custom MATLAB code was developed towards this end. See Appendix G for the specific MATLAB code and scripts.

4.3.1 Task A Data Processing

Task A consisted of the participants fixating on a single point on the center of the HMD screen for 15 seconds. The initial step in data processing the raw signal file converted from the BIOPAC/Acqknowledge system was first segmenting the data according to when the participant was actually performing Task A. For the desired objective, the important factor that needed to be isolated for analysis was the vertical, or z-axis eye movement to observe the effects of z-axis vibration being transferred to the

participants. Figure 20 is an example of the raw vertical eye movement data for the entire duration of the collection for Subject 6 at a frequency of 6 Hz. The following process is a representation of the data processing method for all subjects. Given the time sheet created in the data preparation stage, the start time was input and the MATLAB program segmented the appropriate data. In the case of Task A, the data was segmented from the input time plus an additional 15000 points, or 15 seconds of data collections at 1000 Hz. The relevant time segment for Subject 6 is seen in Figure 20 and indicated by the data between the dotted vertical lines.

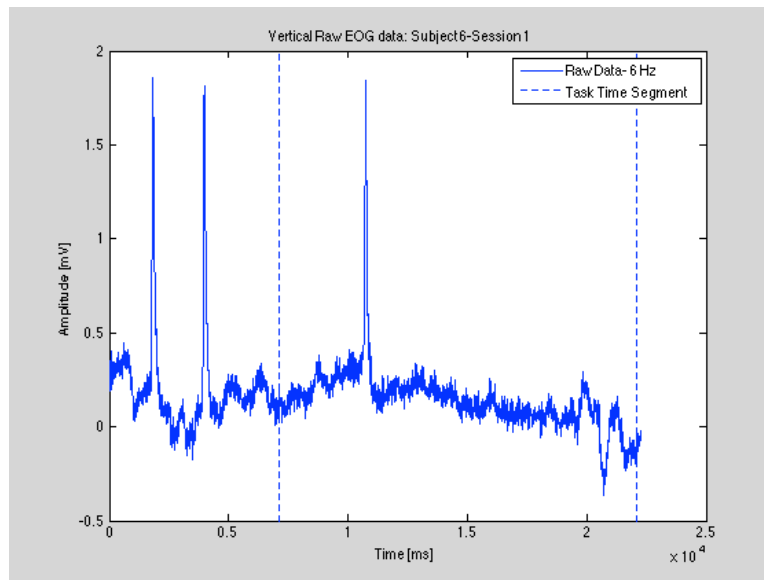


Figure 20. Raw Vertical Data

Given the relevant time segment in which the participant performed the fixation task, a couple observations were made for this raw segment. First, noise attributed to the EOG collection. Second, noise in the form of a low frequency variation within the signal was also readily evident (below the targeted input frequency). Furthermore, two large amplitude eye movements occurred in the time segment of interest. First, a large

amplitude spike in the positive y-direction appeared early in the segment at approximately 1s. This type of spike is seen in nearly every data set when looking at the vertical direction and represents a blink. When a person blinks, the eyes rapidly shift upward and then back down towards their original position, although there is a settling period as the eye will often go below the original starting position. As seen in the figure, these blinks and their respective settling times had a total duration of 100-400 ms. Finally, a less severe but still larger amplitude spike was observed in the negative y-direction at the approximately 2s mark. This was not a blink because of the movement in negative, or down, direction and the lower magnitude of severity indicates that at this point the subject briefly lost fixation and looked down slightly. Thus the large amplitude values seen in these small time segments of blinking and looking down, as well as the drift from the EOG certainly have the potential to have a significant effect on data and must be filtered to permit estimation of the eye movements due to the VOR.

To eliminate the slow drift from the data, a filter employing a moving average was implemented. In this approach, a moving average is created by convolution of a defined filter window and the raw data series. The average of the subset within the fixed window is obtained and then the window shifts forward to the next point and continues forward through the entire data series, averaging the new sets of numbers for the entire process. The line connecting these average values is defined as the moving average. The moving average acts as a low-pass filter on the data by removing the higher frequency noise and smoothing out the data series. The resulting low pass signal can then be subtracted from the raw data to remove the noise in the form of low frequency variation.

The size for the window filter was determined by testing various values and comparing them to the raw data to see how well it followed the series over a diverse section of participant data, to include different tasks and frequencies. As seen in Figure 21, a filter size of 250 points (250 ms) was able to capture most of the signal; however, in larger drop-offs the moving average as not as robust. Using a smaller filter size saw a moving average that did not follow the signal closely, while a larger size cutoff too many of the higher frequencies, shifting the power noticeably to the lower frequency spectrum. Therefore a window size of 250 points was applied in this step. The resulting moving average was subtracted from the raw vertical data to create a new, filtered vertical data set.

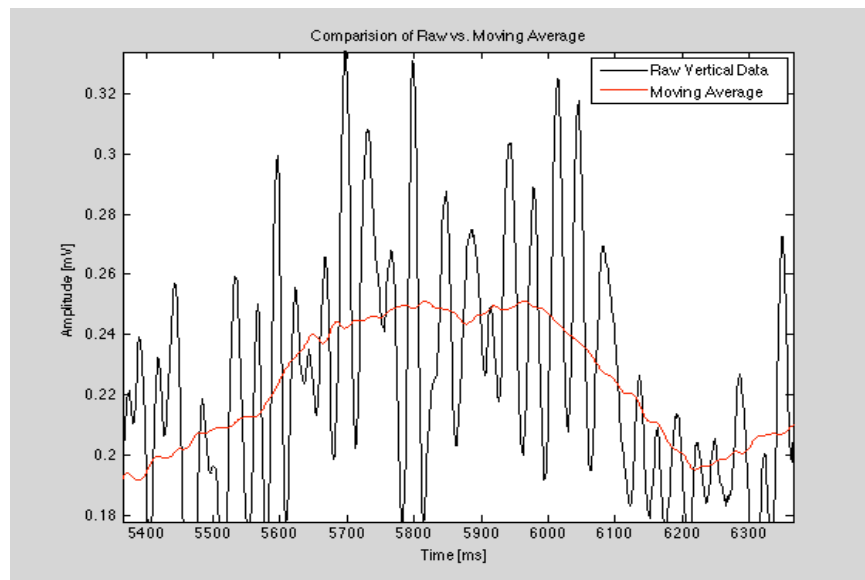


Figure 21. Moving Average of Raw Data

The resulting plot from applying the moving average filter appears in Figure 22. As can be seen in the figure, the slow drift has been removed from the raw data set; however, the blink is clearly visible, and in fact, accentuated by the moving average

filter. Also, less visible but still noticeable is the effect of the brief downward eye movement which can be seen as a slight sinusoid at the end of the data series (12000-15000 ms). These segments still needed to be filtered, as their magnitude values would certainly skew the data. The implementation of several methods to eliminate the blinks and erroneous eye movements of the participants were attempted with little success. Keeping in mind the goal of analyzing the effect of vibration on fixation, the determination was to create an upper and lower amplitude value bound of acceptable eye motion. To set the limits, a representative section in which the participant was clearly fixating needed to be selected. However, obviously this could not be taken over a fixed time for each participant as each behaved differently and each had blinks or other eye movements at different times. Therefore, the program prompted for the selection of this representative segment for each participant and their individual data sets for frequencies. Figure 22 shows an example of selecting the representative data to set the limits. Between 4.5 and 11.5 seconds, Subject 6 was fixating properly on the target and thus the max and min bounds of amplitude value were determined from this section. Any values outside these limits were cut and the result was a final filtered vertical data array. This filtering process is not a refined method and can only be applied to fixation tasks because any vertical eye movement outside of the set boundaries of fixation is inappropriate to analyzing the actual fixation. Incorporating this method into data from tasks that required vertical motion would not be feasible as setting the limits could eliminate necessary vertical eye motions.

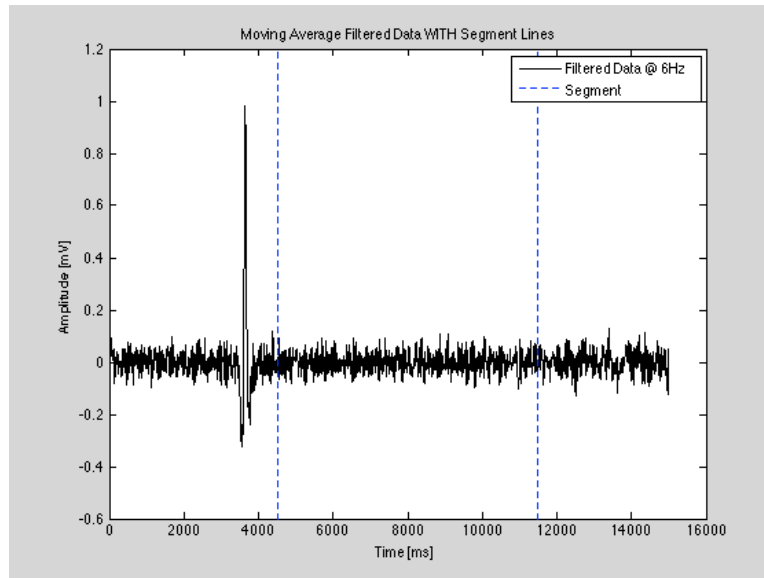


Figure 22. Filtered Data with Time Segments selected

Having filtered out the slow-drift with a moving average filter and eliminated blinks and other erroneous eye motions with a fixation sample filter, the participant's data was prepared for analysis. The eye movement measure selected was the root mean square (RMS) value of the voltage potential (mV) at the frequency at which the specific data was collected. The RMS value was calculated by running the final filtered data through a loop in which the RMS was calculated using Welch's method (Diez, 2008), which estimates the power spectral density estimate (PSD) at different frequencies using an overlapping window principle and computing the discrete Fourier Transform. The resulting array was the RMS value vs. frequency. As seen in Figure 23, for Subject 6's vertical eye motion data in Task A at the 6 Hz condition, the peak of the PSD occurred at the expected 6 Hz. The mV RMS value at the tested frequency for each subject was recorded for analysis.

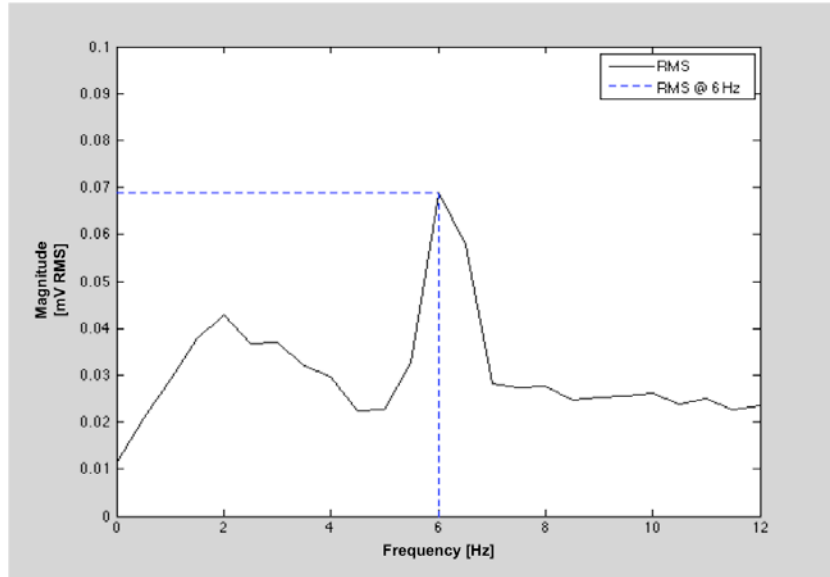


Figure 23. RMS vs. Frequency for Task A

4.3.2 Task B Data Processing

Task B required the participants to fixate on a smooth moving target as it followed a set motion path for the 6 test conditions. To focus on the fixation part of this task, only the segments where the participant was tracking the target horizontally were analyzed as this allowed the vertical RMS signal to be compared to the RMS signal for the fixation point task in Task A. This analysis was acceptable as no voluntary vertical eye motion should exist in this task and thus the effect of vibration in the most severe, z-axis could be analyzed for simple fixations.

The processing of the data for Task B followed the same procedure as Task A with one major addition. The data in Task A could be filtered and analyzed over the entire collection segment, but with Task B, the data set was parsed to include only the vertical eye motion data for the horizontal tracking segments. Given that each of the subjects were shown the same motion path for each test session and each individual

frequency and the timing of the motion was known, the data was parsed according to time. The four horizontal motion segments then were combined into one array of vertical eye data for the horizontal segments. This array was filtered with the same process as followed in Task A and the RMS values for each subject at each frequency was calculated in the same fashion.

4.4 Data Analysis

4.4.1 Outliers

The processing and calculation methods described in the previous section resulted in an array of RMS values for each subject at each frequency for both test sessions for both Task A and B. All of the RMS values for all subjects were plotted for each individual task to acquire an initial, visual observation of the behavior of the vertical eye motions in a fixation mode. The resulting plot for Task A is shown in Figure 24, while the plot for Task B is shown in Figure 25.

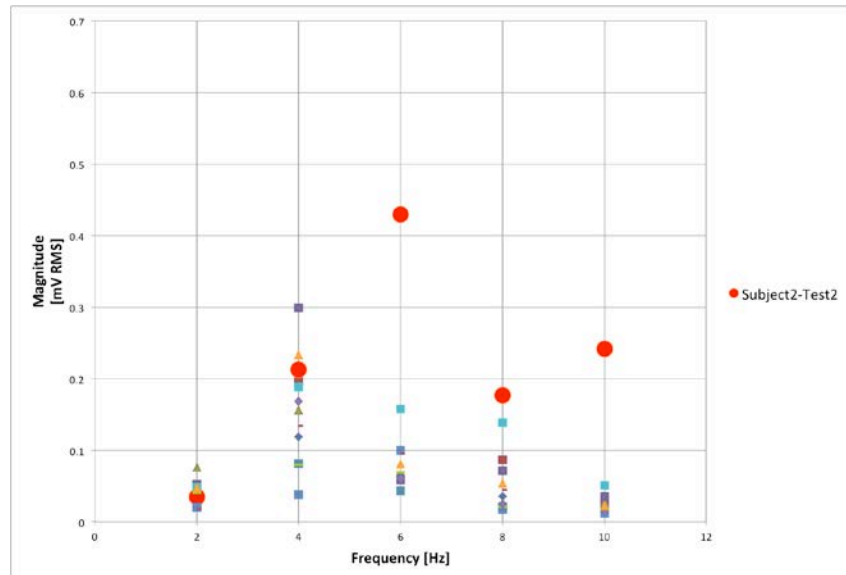


Figure 24. Outlier Data: Task A

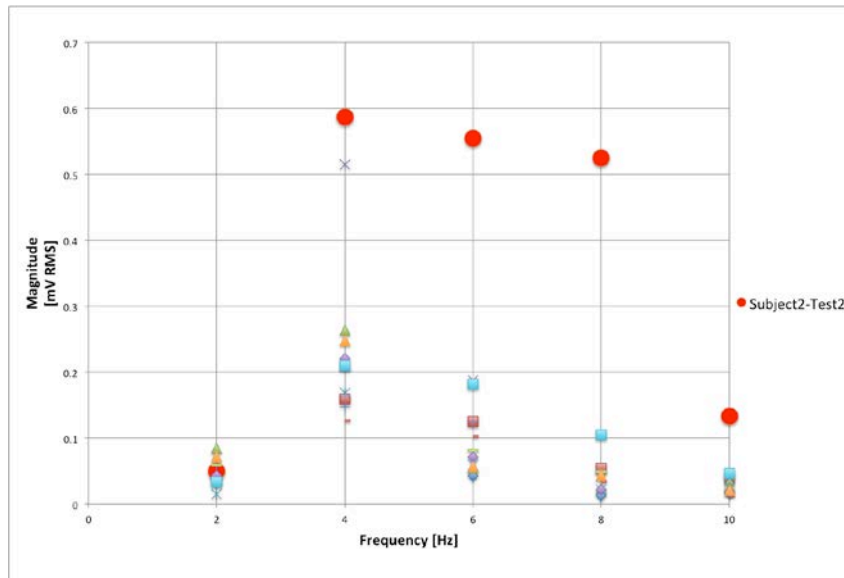


Figure 25. Outlier Data: Task B

Examination of the two plots showed similar trends that will be discussed in more detail in following sections; however, the preliminary concern was several points of data that appeared to be outliers in the data. Eliminating any data, even if the response is not necessarily what is expected or seems wrong, is not to be considered without significant justification. As shown in Figures 24 and 25, the outlying points were nearly exclusively from Subject 4's 2nd Test. A closer investigation into these points was conducted by analyzing the eye video files at these segments. Upon examination of the files, there did not appear to be any eye movements out of the ordinary and the eye movements for this 2nd test did not appear to differ significantly from the first test, despite the dramatic difference in amplitude as measured with the EOG. Thus, it was decided that the EOG may not have made acceptable contact or have been placed appropriately during this session and the data for the 2nd session of Subject 4 was removed from the subsequent analysis.

4.4.2 Task A Results

Given the multiple sources of variation (Subject, Frequency, Test Session) an analysis of variance (ANOVA) was applied to understand which of these effects had a significant influence on the RMS value. A least squares method, specifically a restricted maximum likelihood (REML) approach, was chosen to create the ANOVA model as this method permitted the analysis to be performed with the missing data points for Subject 4's second session. Statistical software developed by JMP was used to conduct this analysis. The ANOVA was setup with RMS as the dependent, or response variable. The model effects consisted of Subject, Frequency and Session and all of the interactions, or crosses, between these fixed variables. Subjects were treated as a random effect within the model.

Executing the ANOVA resulted in a fixed effects table detailing the impact that the fixed variables in the model had on the RMS value. The analysis program conducted an F-test on the data to compute an F-statistic and a p-value. The p-value is defined as the probability of obtaining a value higher than the F-statistic by chance alone. This value was the focus of the analysis, as a p-value ≤ 0.05 infers that the association between the response variable and the fixed variable are statistically significant. The ANOVA indicated that only the effect of Frequency was statistically significant ($F(4, 20.76) = 23.29, p < 0.0001$).

In order to further understand this interaction, a post hoc Tukey's Honestly Significant Difference (HSD) test was applied to the 5 frequency values to determine statistically significant differences between the levels. The Tukey test used applied a 95% confidence interval ($\alpha = .05$) and calculated the Least Square Means (LSM) of the

subject's data at each frequency. The results for the Tukey Test are seen in Table 4, which lists the frequency in the order of the LSM value. The resulting means for Task A at each frequency from the Tukey test with the corresponding standard error are shown in Figure 26.

Table 4. Tukey Test Results: Task A

Frequency	Interactions			LSM
4	A			0.1567
6		B		0.0735
8		B	C	0.0487
2		B	C	0.0382
10			C	0.0246

Levels not connected by the same letter are significantly different

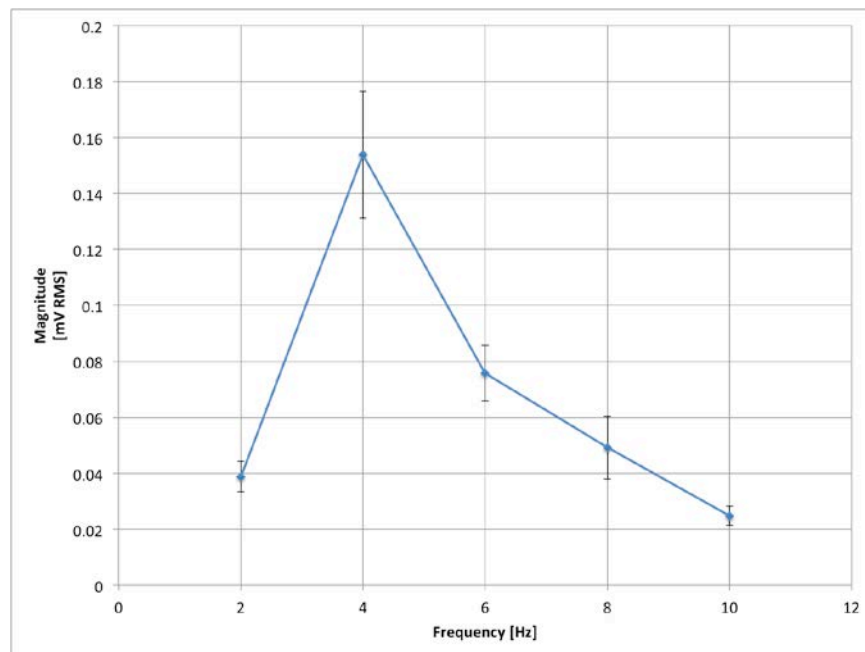


Figure 26. RMS Means with Standard Error Plot for Task A

The important observation to be noted from this test was the interactions between the frequencies. Frequencies with the same letter were not significantly different, while those that did not share the same letter were significantly different. For Task A, the RMS

data at 4 Hz was significantly different from the other 4 test points, while 6 Hz was significantly different only from the 4 and 10 Hz conditions. Figure 26 displays these interactions and shows that the RMS value increases dramatically from the 2 to 4 Hz condition and then decreases with further increases in frequency.

4.4.3 Task B Results

As in Task A, only the effect of Frequency was significant ($F(4, 20.93) = 22.57$, $p < 0.0001$). The results of the Tukey test for Task B are displayed in Table 5 and shows that the results for this analysis were the same as in Task A. The means from this analysis and their standard errors are plotted in Figure 27 once again showing that the RMS value is highest for a frequency of 4 Hz and decline for both lower and higher frequencies.

Table 5. Tukey Test Results: Task B

Frequency	Interactions			LSM
4	A			0.223
6		B		0.099
2		B	C	0.0463
8		B	C	0.0388
10			C	0.0272

Levels not connected by the same letter are significantly different

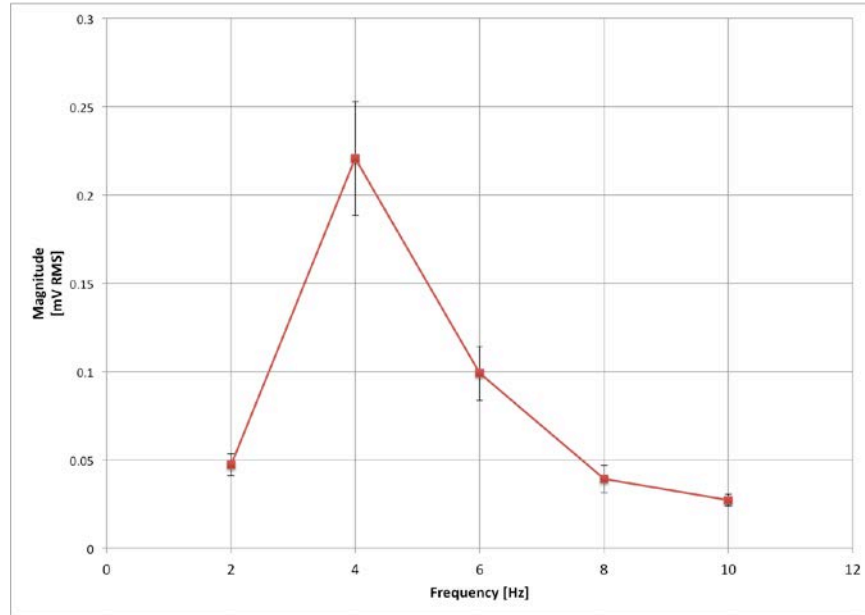


Figure 27. RMS Means with Standard Error Plot for Task B

4.4.4 Task Comparison Results

Since both Task A and B were fixation modes, Task A observing a participant's fixation of a stationary, single target and Task B requiring the participant to fixate on a moving, single target, the next step in analysis was to structure the data to permit the two tasks to be compared against each other to determine the effect, if any, of the different tasks on the RMS value. The data sets were combined, while still omitting Subject 4's Test 2 data for both tasks. The analysis of comparing the tasks followed the same general procedure as when analyzing the individual tasks. The same ANOVA model used for Task A and B analysis was applied to the comparison test; but included the effect of Task and the interaction of task with the three other fixed variables. As one would expect based upon the earlier analysis, the effect of Frequency was significant ($F(4, 20.97) = 26.20, p < 0.0001$).

The effect of Task neared but was not significant ($F(1, 5.25) = 5.84, p \leq 0.058$). Of greater interest was the fact that the Frequency*Task cross-term was statistically significant ($F(4, 20.72) = 6.14, p \leq 0.002$). A Tukey post hoc test was conducted on the frequency interaction with the RMS value with the results outlined in Table 6. Similarly to the results for the individual analyses, the RMS value was statistically higher for a frequency of 4 Hz than for any other frequencies. Further, frequencies of 6, 8, and 2 were significantly different than the RMS values for 10 Hz and values at frequencies 8, 2, and 10 were lower than at 6 Hz.

Table 6. Tukey Test Results: Combined Comparison

Frequency	Interactions		
4	A		
6		B	
8		B	C
2		B	C
10			C

Levels not connected by the same letter are significantly different

Figure 28 shows the Frequency* Task interaction. As shown in this figure, the RMS value for Task B appears to be higher than the RMS value for Task A for the most sensitive frequencies (4 and 6 Hz) but not for the other frequencies. To analyze this interaction, a new ANOVA model needed to be created for each frequency. This was accomplished by first sub setting the data according to frequency, which then required a change in the ANOVA model. Since the ANOVA was being run for each frequency individually, frequency was no longer used as a fixed effect. Thus, the fixed effects were Subject (still random), Session and Task, with the response variable remaining as the

RMS value. The same LMS method was used for this ANOVA. The ANOVA was applied to each of the 5 frequencies and resulted in 5 different fixed effects tables.

However, per the first ANOVA results, the interaction that was of importance in this analysis was the impact of Task. According to the results, 4 Hz was the only condition at which the association of the task and RMS values was statistically significant ($F(1, 5.27) = 6.71, p \leq .0464$). The condition at 6 Hz was close to the upper bound for statistical significance ($F(1, 4.96) = 4.49, p \leq .0881$) but nothing can be stated with confidence about this condition because the p-value was greater than .05.

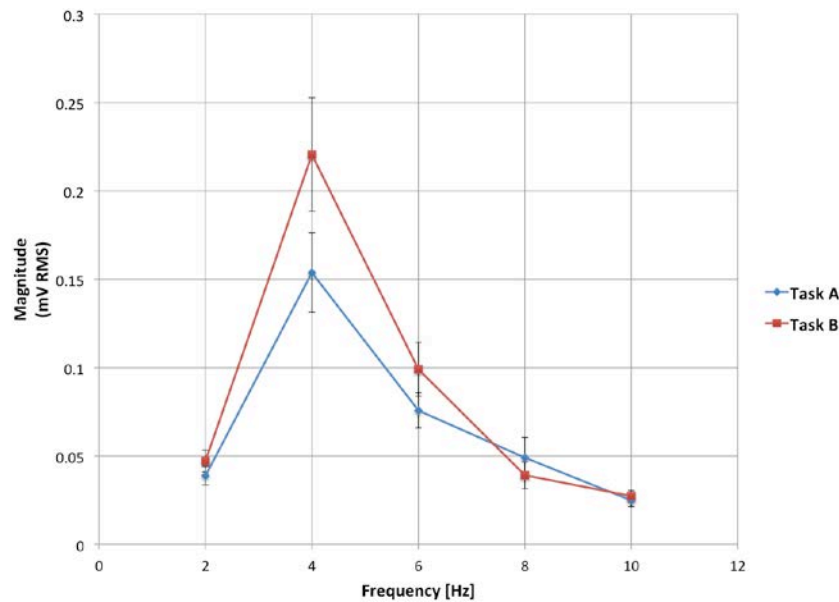


Figure 28. RMS Means with Standard Error Plot for Task A & B

To highlight the significant effect at 4 Hz between the two tasks, Figures 29 and 30 are plots of comparison between the two tasks for an example subject. Figure 29 is a plot of the amplitude of the frequency signal at a specific 2- second fixation segment, post filtering. As seen in the plot, the amplitude for Task B (lower plot) is greater than at

Task A (upper plot), which corroborates the statistical data. Figure 30 is the RMS vs. Frequency plot and gives a clear picture of the significant statistical difference between the two tasks at 4 Hz. The magnitude for Task B is significantly greater than at Task A.

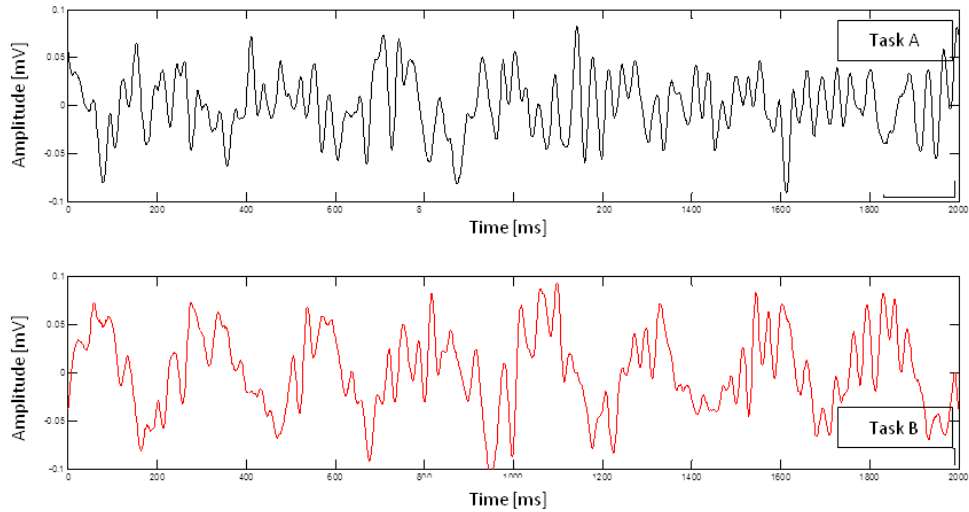


Figure 29. Example Fixation Segment Magnitude for Task A and B @ 4 Hz

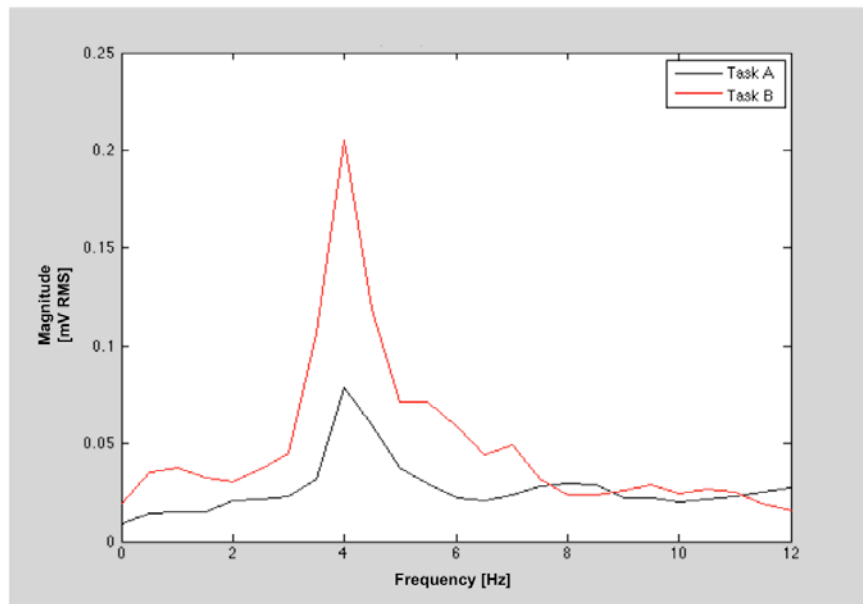


Figure 30. Example RMS vs. Frequency for Task A and B @ 4 Hz

4.4.5 Accelerometer Data

The EOG data analysis results for the comparison of Task A and B found a significant difference at 4 Hz and an increased difference at 6 Hz as well, but verification was necessary to determine if these changes in eye movement magnitudes were the results of changes in frequency and task only and not a difference in input signal frequency amplitude between these two tasks. To determine the amplitude at which the head was vibrating, data were analyzed from the z-axis segment of the accelerometer data for each subject. Since the chair vibration input (specific frequency at .1 g Peak) was held constant for all tasks, the RMS values in the z-axis for head vibration theoretically would be nearly similar for both tasks. Prior to the data being analyzed, Subject 5's Test 1 data were removed from the set because during the experimentation session it had been noted that their accelerometer was not collecting data properly. Evaluation of the data proved this observation as the RMS values were 70 times greater than the mean of the other values.

An ANOVA was applied to the acceleration data with the fixed variables as Subject, Frequency, Test Session and Task and the response variable as the RMS acceleration values. The analysis of the two data found no statistically significant difference between the head vibration amplitude at Tasks A and B. Figure 31 shows the means of the RMS acceleration values plotted for both Tasks A and B. An observation of note from the graph was that the highest RMS values occurred at 4 and 6 Hz, with the highest peak in vertical head acceleration occurring at 6 Hz instead of at 4 Hz as found in the eye motion data. The results from a post-hoc Tukey test from the ANOVA analysis are displayed in Table 7 and show that although there was a statistical difference between

6 Hz and 2, 8 and 10 Hz. there was no statistical difference between RMS acceleration values at 4 and 6 Hz. There was also no statistical difference between 4 Hz and 2,8 and 10 Hz.

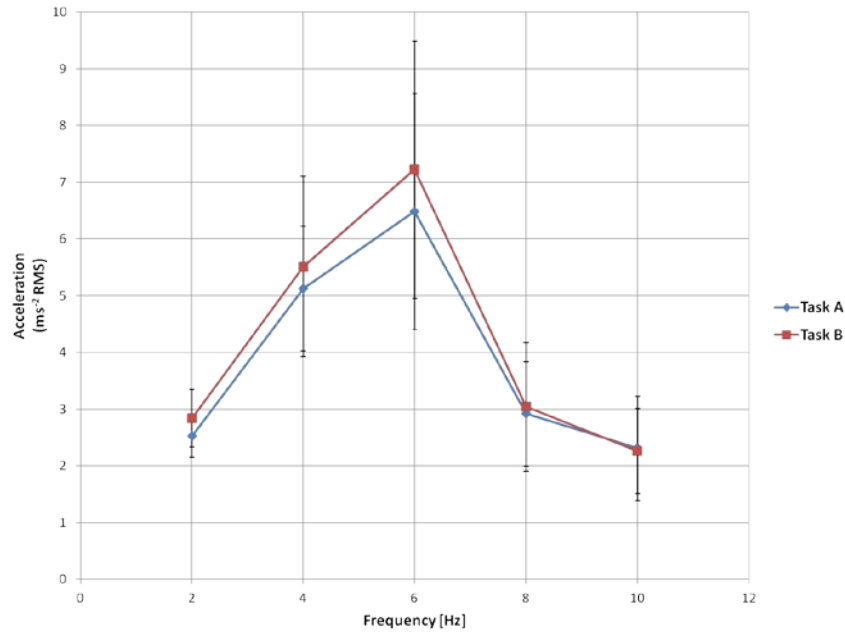


Figure 31. Mean RMS and Error for Z-Axis Head Vibration

Table 7. Tukey Test Results: Z-axis Head Acceleration

Frequency	Interactions		LSM
6	A		7.07
4	A	B	6.02
8		B	3.11
2		B	2.68
10		B	2.38

Levels not connected by the same letter are significantly different

4.5 Discussion of Results

4.5.1 Task A and B

The result from the ANOVA test verified that, as expected, frequency had a statistically significant impact on the RMS values of eye motion. However, the post hoc Tukey test gave a more in-depth analysis on the details of this association. It found that the mean at the peak of 4 Hz was statistically different from all the other frequencies, 6 Hz was different from the 10 Hz condition, while other conditions were not statistically different. Figure 27 displays this trend for both Task A and B. Both tasks saw a sharp increase from 2 Hz to a mean RMS peak at 4 Hz while decreasing again incrementally from 6 Hz down to the low mean RMS value at 10 Hz. Both statistical and graphical observations verified that 4 Hz had the greatest impact on the vertical eye movement followed in magnitude by 6 Hz, which had a more significant impact than the other frequency conditions.

An initial hypothesis would have expected the largest magnitudes to occur at 4 and 6 Hz. This derived from research finding an increase in aiming error and acuity decrements (Velger, 1998) as well as a rise in reading errors (Wells and Griffin, 1990) at this range. Additionally, research literature suggested that as the frequencies increased beyond 6-8 Hz into the higher frequency regime, the body would be more successful at dampening the vibration and decreasing the transfer to the head (Paddan and Griffin, 1988).

Until now, research analyzing the impact of the VOR on visual performance in vibration conditions had relied only on performance measurements such as reading or aiming errors. The results of the Task A and B analysis from collected eye movement

magnitude data (in mV) confirmed the findings of previous performance research. The highest RMS values did in fact occur at this 4-6 Hz range, while steadily decreasing with increasing frequency. The 10 Hz vibration condition having the lowest impact on the magnitude of eye movement for both tasks proved these findings. Overall, the findings for analysis performed on each individual task found that the RMS amplitude of the vertical eye movements as a function of frequency followed the same general pattern derived from performance measures.

4.5.2 *Comparison of Tasks*

The first two analysis sections focused on determining the fixed effects impacts on the RMS values individually as separate tasks. As discussed in the previous section, frequency had a significant impact on eye movement, with the peak influence occurring at 4 Hz and a lesser impact occurring at 6 Hz for both tasks. Given this relationship between eye movement and frequency, the last section of results looked at investigating an association, if any, between eye movement and the type of task being performed by the participant. An initial ANOVA of the combined data set found that the Frequency*Task relationship had a significant impact on the response variable. The post hoc analysis on each individual component of frequency yielded interesting results. The data indicate that accomplishing a fixation on a moving target as opposed to a stationary target did not have a significant impact on eye movement at 2, 8 or 10 Hz. However, the analysis found that a significant difference in vertical eye movement between tasks occurred at 4 Hz and borderline significance occurred at 6 Hz.

This comparison of tasks confirmed that the 4-6 Hz conditions are the most destructive as indicated in the data previously mentioned research although the previous

research had not distinguished between specific eye tasks, such as a moving fixation versus a stationary one. Of importance was the finding that the VOR effect resulted in larger amplitude eye movement when fixating on a target in motion as opposed to fixating on a stationary target. This indicates that adding any complexity to a task, even something as simple as smooth motion, has a significant impact on the magnitude of eye motion in this 4-6 Hz range.

Finally, the measured z-axis, or vertical, head acceleration values confirmed that the vibration at the head was not significantly different between the two tasks, which was expected because of the consistent frequency signal being inputted to the chair across tasks. Additionally, the RMS acceleration value peak at 6 Hz was not significantly different than the acceleration RMS value at 4 Hz. However, the value at 4 Hz was not significantly different than any of the other values suggesting that the VOR, relative to head acceleration, was more sensitive at the 4 Hz condition at which the EOG data saw the highest peak.

Considering that the EOG measured eye displacement (in mV), an estimation of the head displacement was done to determine if the VOR was sensitive to displacement rather than acceleration at low-frequencies. Figure 32 shows the calculated head displacement from the means at Task A and B. As seen, 2 Hz had the highest displacement, but as research has shown, the fixation reflex is effective at 1-2 Hz (Griffin, 1990). The next highest displacement occurred at 4 Hz, which corroborates with the highest peak in eye magnitude data analyzed in this study. A decrease in displacement with increasing frequency also supports the findings in which the eye movement

magnitudes decreased beyond 4 Hz. These results would imply that the VOR is in fact more sensitive to displacement, as opposed to acceleration at the low-frequency regime.

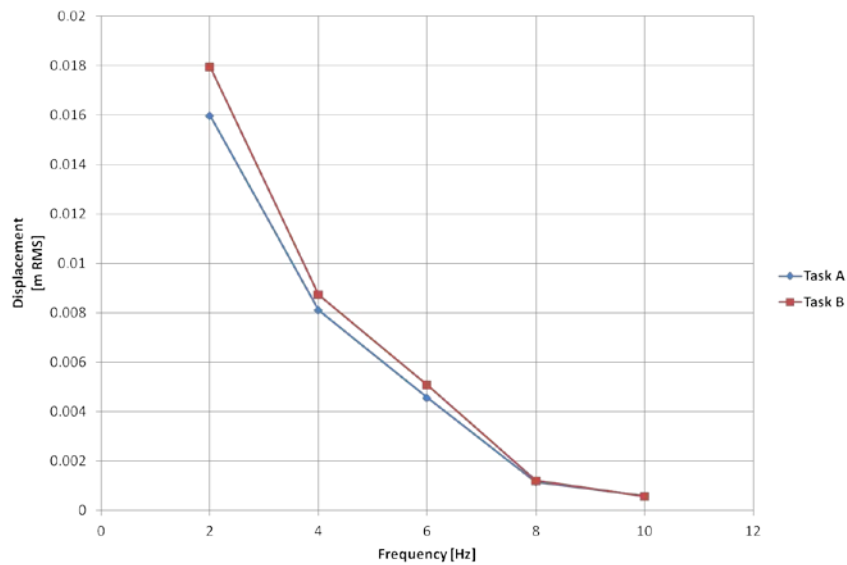


Figure 32. Head Displacement vs. Frequency

Further research is needed to determine if indeed a correlation exists between the head amplitude and eye movement data and needs to include a measurement of head acceleration and displacement pitch, as the VOR is dependent on rotation (Smith and Smith, 2006).

Chapter 5 - Conclusion

5.1 Chapter Overview

Chapter 5 serves as an overall summary of the entire research endeavor starting from the conception of the purpose and goals of the investigation and ending with the discussion of the analysis of the data collected. In this section, the investigative questions posed in Chapter 1 are revisited and answered in accordance to the result found from the data analysis conducted in Chapter 4. Finally, Chapter 5 concludes with an outline of potential future research to be conducted in this area of understanding the VOR and creating an apparatus to combat its negative effects on HMD performance.

5.2 Summary of Research

5.2.1 Literature Overview

The detrimental effect of vibration on human performance, especially in visual tasks, has been a well-documented problem over the last several decades. In the arena of Helmet Mounted Displays, the issue of vibration had been acknowledged but largely ignored for several years for a variety of reasons, perhaps chief of which was that many of the weapon platforms utilizing HMDs did not see the operator encountering vibration levels at which there was a noticeable drop in performance. However, today's military has seen an increased prevalence of Helmet Mounted Displays in not only fixed-wing aircraft, but in rotary aircraft, ground based vehicles, and even systems utilized by individual ground forces. Research indicates that the low-frequency vibration region is where performance suffers most, specifically in the 4-6 Hz range. The issue of vibration and its associated effects have been brought back to the forefront as this low-frequency

regime is one in which many of the newer platforms and personnel, utilizing HMDs operate in, whether from vibration from rotors or movements induced from running.

The reason for the drop in visual performance when operating in these low-frequency areas is the natural Vestibulo-Ocular Reflex. The VOR compensates for head motion to visually stabilize the world. This is an extremely necessary and powerful reflex, as it allows one to be able to accomplish tasks as simple as reading or writing, by correcting for even slight motions of the head by moving the eyes at an equal and opposite magnitude from the head movement. However, when utilizing an HMD, this reflex becomes inappropriate as the display is also moving with respect to the head. The effect of the eye being stabilized by the VOR but the display still vibrating is akin to attempting to read information or track a target on a shaking screen while sitting in a stationary chair.

5.2.2 Research Purpose and Goals

While the effect of the VOR under vibration conditions is well known, limited research has been done in terms of compensating for it. Many of the compensation algorithms developed are latent and inaccurate due to the number of input signals required. Therefore, the overall purpose of this area of research is to conduct an investigation into the VOR to understand its effects and develop compensation algorithms based solely on this effect. The goals of this specific research project was to develop an apparatus to collect eye motion data, develop and conduct an experiment simulating tasks encountered when using a typical HMD, and begin an initial analysis into the data collected to establish a baseline for future VOR research.

5.2.3 *Apparatus Design*

An HMD system was needed that would not only allow participants to perform visual tasks but also one that could record and track the movements of the participant's eye. Therefore a custom HMD was designed and built over several iterations to accomplish this goal. Additionally, it was devised to accommodate six electrodes used to measure the movement of the eyes with respect to the head via Electro-Oculography. Finally, participants were fitted to a custom bitebar with an attached accelerometer to measure head acceleration. Tasks were projected to the participant via a binocular display incorporated in the helmet's visor. This visor, and the various tracking equipment built on to it, was designed to be used universally on a standard flight helmet to provide best fit for subjects.

The final HMD product used during testing was able to achieve many of the requirements set forth prior to design; however, it remains far from a finished product. The apparatus was successful in simulating a real-world HMD during the experimentation. Based on post-test questionnaire data, there were limited comments on the inability to see and accomplish the tasks projected on the binocular LCD screen. Also, the camera and IR LED successfully maintained and recorded a constant image of the eye for the duration of the experiment. There were no issues in terms of the robustness of the system even when exposed to frequent low-frequency conditions over the course of the entire experimentation period.

Yet, there remain issues to be addressed with the system. Positioning of the equipment, including the display, camera and IR LED was locked down to one location with the relative inability for any adjustability. With the focus being on the participants

being able to see the display to perform the task, moving the visor up and down allowed them to position the visor in the correct position relative to their specific head size and eye position. However, this impacted the image of the eye being captured. Early design work found the positioning of the camera and IR LED was vital to capturing a clean image. Having the ability to adjust all aspects of the system to the specific user will allow a sharper image of the corneal reflection and pupil to be captured and thus making eye tracking and analyzing much more efficient and accurate.

5.2.4 Experiment Design and Execution

Considering the goal of establishing a baseline for further research, the experiment was simplified in several ways. The facility used for testing was a single-axis vibration table and therefore participants were only subjected to vertical, or z-axis, vibration at a single frequency for each condition. However, this condition, as described in research, has the most significant effect on visual performance because of the whole-body resonance identified during exposure to vertical vibration, and the amplification of this vibration at the head. . The tasks also were simplified to isolate specific eye motions. The tasks looked at fixation on a stationary target and tracking a moving target, as well as collecting data on rapid eye motions moving from one target to another. Each task was performed at frequencies from 0-10 Hz, in increments of 2 Hz. The six participants were required to test in two separate sessions in which the task order, as well as frequency exposure order, was varied over the two tasks.

5.2.5 Data Collection and Analysis

Given the large amounts of data collected during the course of the experimentation and the time-constraints of this research project, only an initial analysis

was conducted on Task A and B, the stationary fixation and moving fixation tasks respectively. Since, the experiment was conducted in the z-axis only, the data of interest was the vertical eye displacements collected from the EOG data. Additionally, the smooth tracking movements in Task B were only analyzed for those in the horizontal direction. Data was collected for 15-second segments for each task at each frequency condition. This data was processed in MATLAB and filtered using a custom method that involved applying a moving average filter and then utilizing a fixation limits filter, which are both described in Chapter 4. From the resulting processed data an RMS value was calculated for each participant, for each task at each frequency condition. This RMS value represented the magnitude at which the eye moved in the vertical direction at each condition. These RMS values were then run through JMP using developed ANOVA models. Based on results from the ANOVA tests, post hoc analyses were performed on those elements that had a statistically significant impact on the dependent variable, the RMS value.

5.2.6 Data Analysis Results

Cited research had noted degradation in visual performance in the 4-6 Hz range, with an increase in performance past this range as the frequency increased due to the body being able to absorb more of the higher frequency signals. Therefore, there was expected to be an increase to a peak in calculated RMS values around 4-6 Hz and then a steady decrease in subsequent higher frequencies. As described in Chapter 4, the data in both Task A and B followed this same expected trend. Both analyses found that frequency had a statistically significant impact on the RMS value. Statistically and graphically, both also saw a sharp increase in mean RMS amplitude to a peak at 4 Hz

with a consequent steady decline to a low mean RMS amplitude as the frequency was increased to 10 Hz. The condition at 4 Hz was statistically different from all other conditions, with 6 Hz being borderline significant. As stated, this held true for both fixation on a stationary target and fixation on a horizontally moving target. Comparison analysis on the two tasks found that the Frequency*Task interaction had a statistically significant impact on the dependent variable. Further post hoc analysis on each individual frequency found a statistically significant difference in the mean RMS at 4 Hz and borderline difference at the 6 Hz condition for a stationary and moving fixation task. These results indicated that adding complexity, or movement, to the task significantly increased eye motion magnitude in the vertical direction in that detrimental 4-6 Hz range. The analysis of both the individual tasks and the consequent comparison of both tasks verified past human performance research results in which it has been substantiated that reading and aiming accuracy is lowest in the 4-6 Hz range. Quantitative eye movement data analyzed in this study saw the greatest eye movement magnitude values at 4-6 Hz with a steady decrease with increased frequency and an increase in magnitude in this range with the introduction of motion to the task. As a result of these initial findings, any compensation system will need to especially account for this region of low frequencies. Furthermore, the finding that adding in simple motion made a significant difference in the magnitude of eye motion suggests that a compensation system will also need to consider the visual task that the user is attempting to accomplish. However, adding to the complexity of this issue is the large variation in RMS magnitude values between subjects found at 4-6 Hz. Simply incorporating a mean value is not the solution as this research has proven that eye movement is impacted by specific frequencies as well as the task

being performed and finally is also user dependent, which can be attributed to many factors including body weight and posture.

5.3 Investigate Questions Answered

What equipment can be used to track and analyze the VOR?

The experimental HMD developed worked successfully to provide a participant with a system representative of a real-world system while requiring them to perform simple tasks based on the specific eye motions used in various, more complex tasks. As seen from the results, the eye movements during each of these tasks were successfully tracked with EOG. Though the results were noisy, analysis of the signal found that the eye movement data corresponded with several decades of research investigating the effect of vibration on human performance, with highest magnitude values in the oft-cited 4-6 Hz range. Additionally, the video eye tracking apparatus was able to successfully record a participant's eye throughout the duration of the session, maintaining a constant corneal reflection and image of the pupil. Analysis of this video was outside the scope of this research and therefore it remains to be seen whether relevant eye motion data can be pulled from the raw video recordings.

How can the VOR be isolated within a simplified vibration environment?

The experiment was developed to simplify not only the vibration environment by introducing only z-axis vibration, but also to simplify the tasks performed by test participants. They were asked to perform a stationary fixation task on a center-fixed target, a fixation task on a smooth moving target over a simple pattern, and quick fixation on rapidly appearing/disappearing targets. The analysis on Task A and B found that the

segments in which the subject was blinking or performed a large voluntary eye movement off of the fixation target could be removed from the fixation segments to isolate the effect of vibration on the VOR during fixation. However, as described in Chapter 4, the process that was developed required significant experimenter interaction. It could only be applied to a fixation task and relied on manual segmentation of blinks and other large eye movements for each individual participant's data. Further research will require substantial improvement to this method to provide an automated response for use in a compensation system. The results from the analysis following the expected research trend, as well as seeing a significant increase in magnitude for 4-6 Hz with movement, showed that this effect could be isolated.

Is it possible that the VOR can be characterized to establish a baseline for future research in more complex settings? And to what extent is the VOR predictable for use in compensation algorithms?

These final two questions posed at the beginning of the research cannot be answered at this early stage of the research and analysis of data. Though the collected eye movements did behave in the trend expected from visual performance research, the variation among subjects especially at 4-6 Hz was significant. Further research is needed before making a general statement about characterization and/or predictability. This research did show that eye movements can be successfully collected and this process can be refined to further the endeavor to characterize and predict the VOR.

5.4 Recommendations for Future Work

The purpose of this research was to build and provide a foundation for future work. Therefore the bulk of this investigation was centered to this end to include designing and developing hardware and software for data collection and analysis and planning and executing a human subject experiment to collect eye movement data, which included navigating a complex Institutional Review Board for approval to conduct this type of study. The analysis conducted on the data was far from comprehensive, but gave an initial look into the trends found in the data. Further research analyzing these specific tasks should conduct a more in-depth examination into the individual subject's behavior and also determine if a correlation between the eye and head movement data exists.

There remains a large amount of unprocessed raw data specifically for the vertical tracking motions in Part B, the jumping target data in Task C and the head vibration data collected from the accelerometer. Additionally, the video files tracking each participant's eye during the duration of both of the test sessions have not been processed. Certainly, much work remains to be done in this area, especially in determining whether the VOR can even be automatically characterized in this simplified environment of single-axis vibration and simple visual tasks. Some modifications are suggested for the current setup. First, there is the need to include appropriate head/helmet measurements to accurately measure pitch in order to relate it to eye motion. Also, as previously discussed, the bitebar accelerometer data indicated that the VOR seemed to be most sensitive to head displacement vs. head acceleration at the low-frequency regime. Further analysis of this relationship is necessary. Furthermore, the tasks may also need modification. Post-test questionnaire comments revealed that patterns became very predictable and may have

impacted the data, especially in Task C. A brief, initial look at Task C data showed that some subjects began their eye movements before the target appeared due to anticipation of the position of the target. A re-run of this same test would need to vary the pattern and motion paths to eliminate that degree of anticipation. Finally, as mentioned, further analysis is required to determine whether a link can be established between VOR effect and vibration.

If this characterization exists and there is a possibility for predictability, then further tests should be conducted in the more complex, real-world vibration environment provided by the SIXMODE facility also located at AFRL. Further tests should also incorporate tasks that go beyond simple fixation and isolated eye movements, but involve real-world tracking and information processing tasks. Eventually, the vision would be to test compensation algorithms incorporating this VOR predictability into live aircraft and HMD systems.

5.5 Final Thoughts

This investigation delved into a research area that until now has been largely overlooked especially in terms of military application; attempting to look at and further understand the compensatory eye movement of the VOR and its effect on visual performance using an HMD in vibration conditions. This research was successful in building an experimental HMD apparatus that allowed for a participant to perform visual tasks, while also capturing and recording the participant's eye movement via video recording and EOG. The design and execution of the experiment was also a significant focus of this research in terms of fostering inter-organizational cooperation for facility

use between AFIT and AFRL, developing tasks for isolating eye motions and collecting and processing data. An initial analysis of the results confirmed decades of performance measure research trends, finding that the eye movement data saw max magnitude RMS values occurring at the 4-6 Hz range, linking to the significant decrease in visual performance at this same range. Additionally, it was determined that fixation on a moving target resulted in a significant increase in eye movement amplitude over a stationary fixation at this 4-6 Hz range. Significantly more analysis remains to be done on not only the raw data collected in this research but also there is room for substantial improvements in the experimental and data processing methodology. However, this investigative effort was able to prove that eye movement data is able to be collected by correlating it with past performance research results and also lay the groundwork for important further research projects in the area of HMDs, vibration and the associated VOR effect.

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Appendix A – Pre-Test Questionnaire

Subject ID:

Age:

Gender:

(Women Only) Are you pregnant or suspect to be pregnant? YES/NO

(Women Only) Do you have breast implants? YES/NO

Do you wear corrective lenses (glasses/contact lenses)? YES/NO

Have you had corrective eye surgery (PRK/LASIK)? YES/NO

Have you been diagnosed or treated for any eye injuries or disease(s)? YES/NO

Have you been diagnosed or treated for any inner ear injuries or disease(s)? YES/NO

Have you experienced any inner ear problems in the past month (vertigo, dizziness, infection)? YES/NO

Have you consumed alcohol in the past 24 hours? YES/NO

Are you currently experiencing or in the past month have experienced:

...cold or allergy congestion symptoms?

YES/NO

... pain in the musculoskeletal system especially in the back or neck?

YES/NO

... Numbness/Tingling/Weakness in Extremities?

YES/NO

... Constant Headaches?

YES/NO

... Shooting Pain into Arms/Hands/Legs/Feet?

YES/NO

If any above are YES, explain below:

Date reviewed:

Signature of research monitor:

Appendix B – Post-Test Questionnaire

Subject ID:

Session #:

HEALTH

Are you experiencing any vestibular issues (dizziness, disorientation, nausea)?
YES/NO

Are you currently experiencing:

... pain in the musculoskeletal system especially in the back or neck?

YES/NO

... Numbness/Tingling/Weakness in Extremities?

YES/NO

... Headaches?

YES/NO

... Shooting Pain into Arms/Hands/Legs/Feet?

YES/NO

If any are YES, please report immediately to an investigator and/or medical monitor

TEST

Next to each of the four tasks RATE from 1-10 (1 being easy, 10 being very difficult), the difficulty of the task.

Task A (Single Target Fixation): _____

Task B (Smooth Target Tracking): _____

Task C (Jumping Target): _____

Also, in the space provided, please write your overall impression of each of the tasks (what made it difficult, easy, boring, etc).

Task A (Single Target Fixation):

Task B (Smooth Target Tracking):

Task C (Jumping Target):

List in order from GREATEST to LEAST, the amount of vibration you experienced in each of these body parts? (Head, Upper Back/Chest, Lower Back/Abdomen, Buttocks, Upper Leg, Lower Legs/Feet)

A diagram consisting of six horizontal lines on the left and a vertical arrow pointing downwards on the right. The horizontal lines are evenly spaced and extend to the right, stopping just before the vertical arrow. The vertical arrow is a single line with a downward-pointing arrowhead at the bottom.

Finally, please provide your overall thoughts/impressions of this experimental session. Please be as detailed as possible.

Appendix C – EOG Data Time Sheets

Subject 2: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test2		
Recording Start	12:50:32	13:06:02	Recording Start	13:02:33	13:18:03
Calibration	12:50:42	12:51:02	Calibration	13:02:43	13:03:03
Task A	12:51:02	12:54:32	Task C	13:03:03	13:06:33
<u>0 Hz</u>	12:51:22	12:51:37	<u>0 Hz</u>	13:03:23	13:03:38
<u>2 Hz</u>	12:51:57	12:52:12	<u>2 Hz</u>	13:03:58	13:04:13
<u>4 Hz</u>	12:52:32	12:52:47	<u>4 Hz</u>	13:04:33	13:04:48
<u>6 Hz</u>	12:53:07	12:53:22	<u>6 Hz</u>	13:05:08	13:05:23
<u>8 Hz</u>	12:53:42	12:53:57	<u>8 Hz</u>	13:05:43	13:05:58
<u>10 Hz</u>	12:54:17	12:54:32	<u>10 Hz</u>	13:06:18	13:06:33
Task B	12:56:47	13:00:17	Task A	13:08:48	13:12:18
<u>0 Hz</u>	12:57:07	12:57:22	<u>0 Hz</u>	13:09:08	13:09:23
<u>2 Hz</u>	12:57:42	12:57:57	<u>2 Hz</u>	13:09:43	13:09:58
<u>4 Hz</u>	12:58:17	12:58:32	<u>4 Hz</u>	13:10:18	13:10:33
<u>6 Hz</u>	12:58:52	12:59:07	<u>6 Hz</u>	13:10:53	13:11:08
<u>8 Hz</u>	12:59:27	12:59:42	<u>8 Hz</u>	13:11:28	13:11:43
<u>10 Hz</u>	13:00:02	13:00:17	<u>10 Hz</u>	13:12:03	13:12:18
Task C	13:02:32	13:06:02	Task B	13:14:33	13:18:03
<u>0 Hz</u>	13:02:52	13:03:07	<u>0 Hz</u>	13:14:53	13:15:08
<u>2 Hz</u>	13:03:27	13:03:42	<u>2 Hz</u>	13:15:28	13:15:43
<u>4 Hz</u>	13:04:02	13:04:17	<u>4 Hz</u>	13:16:03	13:16:18
<u>6 Hz</u>	13:04:37	13:04:52	<u>6 Hz</u>	13:16:38	13:16:53
<u>8 Hz</u>	13:05:12	13:05:27	<u>8 Hz</u>	13:17:13	13:17:28
<u>10 Hz</u>	13:05:47	13:06:02	<u>10 Hz</u>	13:17:48	13:18:03

Subject 3: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:50:05	14:05:35	Recording Start	15:04:26	15:19:56
Calibration	13:50:15	13:50:35	Calibration	15:04:36	15:04:56
Task A	13:50:35	13:54:05	Task C	15:04:56	15:08:26
<u>0 Hz</u>	13:50:55	13:51:10	<u>0 Hz</u>	15:05:16	15:05:31
<u>2 Hz</u>	13:51:30	13:51:45	<u>2 Hz</u>	15:05:51	15:06:06
<u>4 Hz</u>	13:52:05	13:52:20	<u>4 Hz</u>	15:06:26	15:06:41
<u>6 Hz</u>	13:52:40	13:52:55	<u>6 Hz</u>	15:07:01	15:07:16
<u>8 Hz</u>	13:53:15	13:53:30	<u>8 Hz</u>	15:07:36	15:07:51
<u>10 Hz</u>	13:53:50	13:54:05	<u>10 Hz</u>	15:08:11	15:08:26
Task B	13:56:20	13:59:50	Task A	15:10:41	15:14:11
<u>0 Hz</u>	13:56:40	13:56:55	<u>0 Hz</u>	15:11:01	15:11:16
<u>2 Hz</u>	13:57:15	13:57:30	<u>2 Hz</u>	15:11:36	15:11:51
<u>4 Hz</u>	13:57:50	13:58:05	<u>4 Hz</u>	15:12:11	15:12:26
<u>6 Hz</u>	13:58:25	13:58:40	<u>6 Hz</u>	15:12:46	15:13:01
<u>8 Hz</u>	13:59:00	13:59:15	<u>8 Hz</u>	15:13:21	15:13:36
<u>10 Hz</u>	13:59:35	13:59:50	<u>10 Hz</u>	15:13:56	15:14:11
Task C	14:02:05	14:05:35	Task B	15:16:26	15:19:56
<u>0 Hz</u>	14:02:25	14:02:40	<u>0 Hz</u>	15:16:46	15:17:01
<u>2 Hz</u>	14:03:00	14:03:15	<u>2 Hz</u>	15:17:21	15:17:36
<u>4 Hz</u>	14:03:35	14:03:50	<u>4 Hz</u>	15:17:56	15:18:11
<u>6 Hz</u>	14:04:10	14:04:25	<u>6 Hz</u>	15:18:31	15:18:46
<u>8 Hz</u>	14:04:45	14:05:00	<u>8 Hz</u>	15:19:06	15:19:21
<u>10 Hz</u>	14:05:20	14:05:35	<u>10 Hz</u>	15:19:41	15:19:56

Subject 4: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	16:08:28	16:23:58	Recording Start	14:23:07	14:38:37
Calibration	16:08:38	16:08:58	Calibration	14:23:17	14:23:37
Task A	16:08:58	16:12:28	Task C	14:23:37	14:27:07
<u>0 Hz</u>	16:09:18	16:09:33	<u>0 Hz</u>	14:23:57	14:24:12
<u>2 Hz</u>	16:09:53	16:10:08	<u>2 Hz</u>	14:24:32	14:24:47
<u>4 Hz</u>	16:10:28	16:10:43	<u>4 Hz</u>	14:25:07	14:25:22
<u>6 Hz</u>	16:11:03	16:11:18	<u>6 Hz</u>	14:25:42	14:25:57
<u>8 Hz</u>	16:11:38	16:11:53	<u>8 Hz</u>	14:26:17	14:26:32
<u>10 Hz</u>	16:12:13	16:12:28	<u>10 Hz</u>	14:26:52	14:27:07
Task B	16:14:43	16:18:13	Task A	14:29:22	14:32:52
<u>0 Hz</u>	16:15:03	16:15:18	<u>0 Hz</u>	14:29:42	14:29:57
<u>2 Hz</u>	16:15:38	16:15:53	<u>2 Hz</u>	14:30:17	14:30:32
<u>4 Hz</u>	16:16:13	16:16:28	<u>4 Hz</u>	14:30:52	14:31:07
<u>6 Hz</u>	16:16:48	16:17:03	<u>6 Hz</u>	14:31:27	14:31:42
<u>8 Hz</u>	16:17:23	16:17:38	<u>8 Hz</u>	14:32:02	14:32:17
<u>10 Hz</u>	16:17:58	16:18:13	<u>10 Hz</u>	14:32:37	14:32:52
Task C	16:20:28	16:23:58	Task B	14:35:07	14:38:37
<u>0 Hz</u>	16:20:48	16:21:03	<u>0 Hz</u>	14:35:27	14:35:42
<u>2 Hz</u>	16:21:23	16:21:38	<u>2 Hz</u>	14:36:02	14:36:17
<u>4 Hz</u>	16:21:58	16:22:13	<u>4 Hz</u>	14:36:37	14:36:52
<u>6 Hz</u>	16:22:33	16:22:48	<u>6 Hz</u>	14:37:12	14:37:27
<u>8 Hz</u>	16:23:08	16:23:23	<u>8 Hz</u>	14:37:47	14:38:02
<u>10 Hz</u>	16:23:43	16:23:58	<u>10 Hz</u>	14:38:22	14:38:37

Subject 5: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:00:15	13:15:45	Recording Start	13:21:15	13:36:45
Calibration	13:00:25	13:00:45	Calibration	13:21:25	13:21:45
Task A	13:00:45	13:04:15	Task C	13:21:45	13:25:15
<u>0 Hz</u>	13:01:05	13:01:20	<u>0 Hz</u>	13:22:05	13:22:20
<u>2 Hz</u>	13:01:40	13:01:55	<u>2 Hz</u>	13:22:40	13:22:55
<u>4 Hz</u>	13:02:15	13:02:30	<u>4 Hz</u>	13:23:15	13:23:30
<u>6 Hz</u>	13:02:50	13:03:05	<u>6 Hz</u>	13:23:50	13:24:05
<u>8 Hz</u>	13:03:25	13:03:40	<u>8 Hz</u>	13:24:25	13:24:40
<u>10 Hz</u>	13:04:00	13:04:15	<u>10 Hz</u>	13:25:00	13:25:15
Task B	13:06:30	13:10:00	Task A	13:27:30	13:31:00
<u>0 Hz</u>	13:06:50	13:07:05	<u>0 Hz</u>	13:27:50	13:28:05
<u>2 Hz</u>	13:07:25	13:07:40	<u>2 Hz</u>	13:28:25	13:28:40
<u>4 Hz</u>	13:08:00	13:08:15	<u>4 Hz</u>	13:29:00	13:29:15
<u>6 Hz</u>	13:08:35	13:08:50	<u>6 Hz</u>	13:29:35	13:29:50
<u>8 Hz</u>	13:09:10	13:09:25	<u>8 Hz</u>	13:30:10	13:30:25
<u>10 Hz</u>	13:09:45	13:10:00	<u>10 Hz</u>	13:30:45	13:31:00
Task C	13:12:15	13:15:45	Task B	13:33:15	13:36:45
<u>0 Hz</u>	13:12:35	13:12:50	<u>0 Hz</u>	13:33:35	13:33:50
<u>2 Hz</u>	13:13:10	13:13:25	<u>2 Hz</u>	13:34:10	13:34:25
<u>4 Hz</u>	13:13:45	13:14:00	<u>4 Hz</u>	13:34:45	13:35:00
<u>6 Hz</u>	13:14:20	13:14:35	<u>6 Hz</u>	13:35:20	13:35:35
<u>8 Hz</u>	13:14:55	13:15:10	<u>8 Hz</u>	13:35:55	13:36:10
<u>10 Hz</u>	13:15:30	13:15:45	<u>10 Hz</u>	13:36:30	13:36:45

Subject 6: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	15:54:16	16:09:46	Recording Start	15:36:48	15:52:18
Calibration	15:54:26	15:54:46	Calibration	15:36:58	15:37:18
Task A	15:54:46	15:58:16	Task C	15:37:18	15:40:48
<u>0 Hz</u>	15:55:06	15:55:21	<u>0 Hz</u>	15:37:38	15:37:53
<u>2 Hz</u>	15:55:41	15:55:56	<u>2 Hz</u>	15:38:13	15:38:28
<u>4 Hz</u>	15:56:16	15:56:31	<u>4 Hz</u>	15:38:48	15:39:03
<u>6 Hz</u>	15:56:51	15:57:06	<u>6 Hz</u>	15:39:23	15:39:38
<u>8 Hz</u>	15:57:26	15:57:41	<u>8 Hz</u>	15:39:58	15:40:13
<u>10 Hz</u>	15:58:01	15:58:16	<u>10 Hz</u>	15:40:33	15:40:48
Task B	16:00:31	16:04:01	Task A	15:43:03	15:46:33
<u>0 Hz</u>	16:00:51	16:01:06	<u>0 Hz</u>	15:43:23	15:43:38
<u>2 Hz</u>	16:01:26	16:01:41	<u>2 Hz</u>	15:43:58	15:44:13
<u>4 Hz</u>	16:02:01	16:02:16	<u>4 Hz</u>	15:44:33	15:44:48
<u>6 Hz</u>	16:02:36	16:02:51	<u>6 Hz</u>	15:45:08	15:45:23
<u>8 Hz</u>	16:03:11	16:03:26	<u>8 Hz</u>	15:45:43	15:45:58
<u>10 Hz</u>	16:03:46	16:04:01	<u>10 Hz</u>	15:46:18	15:46:33
Task C	16:06:16	16:09:46	Task B	15:48:48	15:52:18
<u>0 Hz</u>	16:06:36	16:06:51	<u>0 Hz</u>	15:49:08	15:49:23
<u>2 Hz</u>	16:07:11	16:07:26	<u>2 Hz</u>	15:49:43	15:49:58
<u>4 Hz</u>	16:07:46	16:08:01	<u>4 Hz</u>	15:50:18	15:50:33
<u>6 Hz</u>	16:08:21	16:08:36	<u>6 Hz</u>	15:50:53	15:51:08
<u>8 Hz</u>	16:08:56	16:09:11	<u>8 Hz</u>	15:51:28	15:51:43
<u>10 Hz</u>	16:09:31	16:09:46	<u>10 Hz</u>	15:52:03	15:52:18

Subject 7: EOG Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:12:45	13:28:15	Recording Start	10:17:58	10:33:28
Calibration	13:12:55	13:13:15	Calibration	10:18:08	10:18:28
Task A	13:13:15	13:16:45	Task C	10:18:28	10:21:58
<u>0 Hz</u>	13:13:35	13:13:50	<u>0 Hz</u>	10:18:48	10:19:03
<u>2 Hz</u>	13:14:10	13:14:25	<u>2 Hz</u>	10:19:23	10:19:38
<u>4 Hz</u>	13:14:45	13:15:00	<u>4 Hz</u>	10:19:58	10:20:13
<u>6 Hz</u>	13:15:20	13:15:35	<u>6 Hz</u>	10:20:33	10:20:48
<u>8 Hz</u>	13:15:55	13:16:10	<u>8 Hz</u>	10:21:08	10:21:23
<u>10 Hz</u>	13:16:30	13:16:45	<u>10 Hz</u>	10:21:43	10:21:58
Task B	13:19:00	13:22:30	Task A	10:24:13	10:27:43
<u>0 Hz</u>	13:19:20	13:19:35	<u>0 Hz</u>	10:24:33	10:24:48
<u>2 Hz</u>	13:19:55	13:20:10	<u>2 Hz</u>	10:25:08	10:25:23
<u>4 Hz</u>	13:20:30	13:20:45	<u>4 Hz</u>	10:25:43	10:25:58
<u>6 Hz</u>	13:21:05	13:21:20	<u>6 Hz</u>	10:26:18	10:26:33
<u>8 Hz</u>	13:21:40	13:21:55	<u>8 Hz</u>	10:26:53	10:27:08
<u>10 Hz</u>	13:22:15	13:22:30	<u>10 Hz</u>	10:27:28	10:27:43
Task C	13:24:45	13:28:15	Task B	10:29:58	10:33:28
<u>0 Hz</u>	13:25:05	13:25:20	<u>0 Hz</u>	10:30:18	10:30:33
<u>2 Hz</u>	13:25:40	13:25:55	<u>2 Hz</u>	10:30:53	10:31:08
<u>4 Hz</u>	13:26:15	13:26:30	<u>4 Hz</u>	10:31:28	10:31:43
<u>6 Hz</u>	13:26:50	13:27:05	<u>6 Hz</u>	10:32:03	10:32:18
<u>8 Hz</u>	13:27:25	13:27:40	<u>8 Hz</u>	10:32:38	10:32:53
<u>10 Hz</u>	13:28:00	13:28:15	<u>10 Hz</u>	10:33:13	10:33:28

Appendix D – Video Data Time Sheets

Subject 2: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test2		
Recording Start	12:50:32	13:06:02	Recording Start	13:02:33	13:18:03
Calibration	12:50:42	12:51:02	Calibration	13:02:43	13:03:03
Task A	12:51:02	12:54:32	Task C	13:03:03	13:06:33
<u>0 Hz</u>	12:51:22	12:51:37	<u>0 Hz</u>	13:03:23	13:03:38
<u>2 Hz</u>	12:51:57	12:52:12	<u>2 Hz</u>	13:03:58	13:04:13
<u>4 Hz</u>	12:52:32	12:52:47	<u>4 Hz</u>	13:04:33	13:04:48
<u>6 Hz</u>	12:53:07	12:53:22	<u>6 Hz</u>	13:05:08	13:05:23
<u>8 Hz</u>	12:53:42	12:53:57	<u>8 Hz</u>	13:05:43	13:05:58
<u>10 Hz</u>	12:54:17	12:54:32	<u>10 Hz</u>	13:06:18	13:06:33
Task B	12:56:47	13:00:17	Task A	13:08:48	13:12:18
<u>0 Hz</u>	12:57:07	12:57:22	<u>0 Hz</u>	13:09:08	13:09:23
<u>2 Hz</u>	12:57:42	12:57:57	<u>2 Hz</u>	13:09:43	13:09:58
<u>4 Hz</u>	12:58:17	12:58:32	<u>4 Hz</u>	13:10:18	13:10:33
<u>6 Hz</u>	12:58:52	12:59:07	<u>6 Hz</u>	13:10:53	13:11:08
<u>8 Hz</u>	12:59:27	12:59:42	<u>8 Hz</u>	13:11:28	13:11:43
<u>10 Hz</u>	13:00:02	13:00:17	<u>10 Hz</u>	13:12:03	13:12:18
Task C	13:02:32	13:06:02	Task B	13:14:33	13:18:03
<u>0 Hz</u>	13:02:52	13:03:07	<u>0 Hz</u>	13:14:53	13:15:08
<u>2 Hz</u>	13:03:27	13:03:42	<u>2 Hz</u>	13:15:28	13:15:43
<u>4 Hz</u>	13:04:02	13:04:17	<u>4 Hz</u>	13:16:03	13:16:18
<u>6 Hz</u>	13:04:37	13:04:52	<u>6 Hz</u>	13:16:38	13:16:53
<u>8 Hz</u>	13:05:12	13:05:27	<u>8 Hz</u>	13:17:13	13:17:28
<u>10 Hz</u>	13:05:47	13:06:02	<u>10 Hz</u>	13:17:48	13:18:03

Subject 3: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:50:05	14:05:35	Recording Start	15:04:26	15:19:56
Calibration	13:50:15	13:50:35	Calibration	15:04:36	15:04:56
Task A	13:50:35	13:54:05	Task C	15:04:56	15:08:26
<u>0 Hz</u>	13:50:55	13:51:10	<u>0 Hz</u>	15:05:16	15:05:31
<u>2 Hz</u>	13:51:30	13:51:45	<u>2 Hz</u>	15:05:51	15:06:06
<u>4 Hz</u>	13:52:05	13:52:20	<u>4 Hz</u>	15:06:26	15:06:41
<u>6 Hz</u>	13:52:40	13:52:55	<u>6 Hz</u>	15:07:01	15:07:16
<u>8 Hz</u>	13:53:15	13:53:30	<u>8 Hz</u>	15:07:36	15:07:51
<u>10 Hz</u>	13:53:50	13:54:05	<u>10 Hz</u>	15:08:11	15:08:26
Task B	13:56:20	13:59:50	Task A	15:10:41	15:14:11
<u>0 Hz</u>	13:56:40	13:56:55	<u>0 Hz</u>	15:11:01	15:11:16
<u>2 Hz</u>	13:57:15	13:57:30	<u>2 Hz</u>	15:11:36	15:11:51
<u>4 Hz</u>	13:57:50	13:58:05	<u>4 Hz</u>	15:12:11	15:12:26
<u>6 Hz</u>	13:58:25	13:58:40	<u>6 Hz</u>	15:12:46	15:13:01
<u>8 Hz</u>	13:59:00	13:59:15	<u>8 Hz</u>	15:13:21	15:13:36
<u>10 Hz</u>	13:59:35	13:59:50	<u>10 Hz</u>	15:13:56	15:14:11
Task C	14:02:05	14:05:35	Task B	15:16:26	15:19:56
<u>0 Hz</u>	14:02:25	14:02:40	<u>0 Hz</u>	15:16:46	15:17:01
<u>2 Hz</u>	14:03:00	14:03:15	<u>2 Hz</u>	15:17:21	15:17:36
<u>4 Hz</u>	14:03:35	14:03:50	<u>4 Hz</u>	15:17:56	15:18:11
<u>6 Hz</u>	14:04:10	14:04:25	<u>6 Hz</u>	15:18:31	15:18:46
<u>8 Hz</u>	14:04:45	14:05:00	<u>8 Hz</u>	15:19:06	15:19:21
<u>10 Hz</u>	14:05:20	14:05:35	<u>10 Hz</u>	15:19:41	15:19:56

Subject 4: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	16:08:28	16:23:58	Recording Start	14:23:07	14:38:37
Calibration	16:08:38	16:08:58	Calibration	14:23:17	14:23:37
Task A	16:08:58	16:12:28	Task C	14:23:37	14:27:07
<u>0 Hz</u>	16:09:18	16:09:33	<u>0 Hz</u>	14:23:57	14:24:12
<u>2 Hz</u>	16:09:53	16:10:08	<u>2 Hz</u>	14:24:32	14:24:47
<u>4 Hz</u>	16:10:28	16:10:43	<u>4 Hz</u>	14:25:07	14:25:22
<u>6 Hz</u>	16:11:03	16:11:18	<u>6 Hz</u>	14:25:42	14:25:57
<u>8 Hz</u>	16:11:38	16:11:53	<u>8 Hz</u>	14:26:17	14:26:32
<u>10 Hz</u>	16:12:13	16:12:28	<u>10 Hz</u>	14:26:52	14:27:07
Task B	16:14:43	16:18:13	Task A	14:29:22	14:32:52
<u>0 Hz</u>	16:15:03	16:15:18	<u>0 Hz</u>	14:29:42	14:29:57
<u>2 Hz</u>	16:15:38	16:15:53	<u>2 Hz</u>	14:30:17	14:30:32
<u>4 Hz</u>	16:16:13	16:16:28	<u>4 Hz</u>	14:30:52	14:31:07
<u>6 Hz</u>	16:16:48	16:17:03	<u>6 Hz</u>	14:31:27	14:31:42
<u>8 Hz</u>	16:17:23	16:17:38	<u>8 Hz</u>	14:32:02	14:32:17
<u>10 Hz</u>	16:17:58	16:18:13	<u>10 Hz</u>	14:32:37	14:32:52
Task C	16:20:28	16:23:58	Task B	14:35:07	14:38:37
<u>0 Hz</u>	16:20:48	16:21:03	<u>0 Hz</u>	14:35:27	14:35:42
<u>2 Hz</u>	16:21:23	16:21:38	<u>2 Hz</u>	14:36:02	14:36:17
<u>4 Hz</u>	16:21:58	16:22:13	<u>4 Hz</u>	14:36:37	14:36:52
<u>6 Hz</u>	16:22:33	16:22:48	<u>6 Hz</u>	14:37:12	14:37:27
<u>8 Hz</u>	16:23:08	16:23:23	<u>8 Hz</u>	14:37:47	14:38:02
<u>10 Hz</u>	16:23:43	16:23:58	<u>10 Hz</u>	14:38:22	14:38:37

Subject 5: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:00:15	13:15:45	Recording Start	13:21:15	13:36:45
Calibration	13:00:25	13:00:45	Calibration	13:21:25	13:21:45
Task A	13:00:45	13:04:15	Task C	13:21:45	13:25:15
<u>0 Hz</u>	13:01:05	13:01:20	<u>0 Hz</u>	13:22:05	13:22:20
<u>2 Hz</u>	13:01:40	13:01:55	<u>2 Hz</u>	13:22:40	13:22:55
<u>4 Hz</u>	13:02:15	13:02:30	<u>4 Hz</u>	13:23:15	13:23:30
<u>6 Hz</u>	13:02:50	13:03:05	<u>6 Hz</u>	13:23:50	13:24:05
<u>8 Hz</u>	13:03:25	13:03:40	<u>8 Hz</u>	13:24:25	13:24:40
<u>10 Hz</u>	13:04:00	13:04:15	<u>10 Hz</u>	13:25:00	13:25:15
Task B	13:06:30	13:10:00	Task A	13:27:30	13:31:00
<u>0 Hz</u>	13:06:50	13:07:05	<u>0 Hz</u>	13:27:50	13:28:05
<u>2 Hz</u>	13:07:25	13:07:40	<u>2 Hz</u>	13:28:25	13:28:40
<u>4 Hz</u>	13:08:00	13:08:15	<u>4 Hz</u>	13:29:00	13:29:15
<u>6 Hz</u>	13:08:35	13:08:50	<u>6 Hz</u>	13:29:35	13:29:50
<u>8 Hz</u>	13:09:10	13:09:25	<u>8 Hz</u>	13:30:10	13:30:25
<u>10 Hz</u>	13:09:45	13:10:00	<u>10 Hz</u>	13:30:45	13:31:00
Task C	13:12:15	13:15:45	Task B	13:33:15	13:36:45
<u>0 Hz</u>	13:12:35	13:12:50	<u>0 Hz</u>	13:33:35	13:33:50
<u>2 Hz</u>	13:13:10	13:13:25	<u>2 Hz</u>	13:34:10	13:34:25
<u>4 Hz</u>	13:13:45	13:14:00	<u>4 Hz</u>	13:34:45	13:35:00
<u>6 Hz</u>	13:14:20	13:14:35	<u>6 Hz</u>	13:35:20	13:35:35
<u>8 Hz</u>	13:14:55	13:15:10	<u>8 Hz</u>	13:35:55	13:36:10
<u>10 Hz</u>	13:15:30	13:15:45	<u>10 Hz</u>	13:36:30	13:36:45

Subject 6: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	15:54:16	16:09:46	Recording Start	15:36:48	15:52:18
Calibration	15:54:26	15:54:46	Calibration	15:36:58	15:37:18
Task A	15:54:46	15:58:16	Task C	15:37:18	15:40:48
<u>0 Hz</u>	15:55:06	15:55:21	<u>0 Hz</u>	15:37:38	15:37:53
<u>2 Hz</u>	15:55:41	15:55:56	<u>2 Hz</u>	15:38:13	15:38:28
<u>4 Hz</u>	15:56:16	15:56:31	<u>4 Hz</u>	15:38:48	15:39:03
<u>6 Hz</u>	15:56:51	15:57:06	<u>6 Hz</u>	15:39:23	15:39:38
<u>8 Hz</u>	15:57:26	15:57:41	<u>8 Hz</u>	15:39:58	15:40:13
<u>10 Hz</u>	15:58:01	15:58:16	<u>10 Hz</u>	15:40:33	15:40:48
Task B	16:00:31	16:04:01	Task A	15:43:03	15:46:33
<u>0 Hz</u>	16:00:51	16:01:06	<u>0 Hz</u>	15:43:23	15:43:38
<u>2 Hz</u>	16:01:26	16:01:41	<u>2 Hz</u>	15:43:58	15:44:13
<u>4 Hz</u>	16:02:01	16:02:16	<u>4 Hz</u>	15:44:33	15:44:48
<u>6 Hz</u>	16:02:36	16:02:51	<u>6 Hz</u>	15:45:08	15:45:23
<u>8 Hz</u>	16:03:11	16:03:26	<u>8 Hz</u>	15:45:43	15:45:58
<u>10 Hz</u>	16:03:46	16:04:01	<u>10 Hz</u>	15:46:18	15:46:33
Task C	16:06:16	16:09:46	Task B	15:48:48	15:52:18
<u>0 Hz</u>	16:06:36	16:06:51	<u>0 Hz</u>	15:49:08	15:49:23
<u>2 Hz</u>	16:07:11	16:07:26	<u>2 Hz</u>	15:49:43	15:49:58
<u>4 Hz</u>	16:07:46	16:08:01	<u>4 Hz</u>	15:50:18	15:50:33
<u>6 Hz</u>	16:08:21	16:08:36	<u>6 Hz</u>	15:50:53	15:51:08
<u>8 Hz</u>	16:08:56	16:09:11	<u>8 Hz</u>	15:51:28	15:51:43
<u>10 Hz</u>	16:09:31	16:09:46	<u>10 Hz</u>	15:52:03	15:52:18

Subject 7: Eye Recording

<u>Event</u>	<u>Start Time</u>	<u>End Time</u>	<u>Event</u>	<u>Start Time</u>	<u>End Time</u>
Test 1			Test 2		
Recording Start	13:12:45	13:28:15	Recording Start	10:17:58	10:33:28
Calibration	13:12:55	13:13:15	Calibration	10:18:08	10:18:28
Task A	13:13:15	13:16:45	Task C	10:18:28	10:21:58
<u>0 Hz</u>	13:13:35	13:13:50	<u>0 Hz</u>	10:18:48	10:19:03
<u>2 Hz</u>	13:14:10	13:14:25	<u>2 Hz</u>	10:19:23	10:19:38
<u>4 Hz</u>	13:14:45	13:15:00	<u>4 Hz</u>	10:19:58	10:20:13
<u>6 Hz</u>	13:15:20	13:15:35	<u>6 Hz</u>	10:20:33	10:20:48
<u>8 Hz</u>	13:15:55	13:16:10	<u>8 Hz</u>	10:21:08	10:21:23
<u>10 Hz</u>	13:16:30	13:16:45	<u>10 Hz</u>	10:21:43	10:21:58
Task B	13:19:00	13:22:30	Task A	10:24:13	10:27:43
<u>0 Hz</u>	13:19:20	13:19:35	<u>0 Hz</u>	10:24:33	10:24:48
<u>2 Hz</u>	13:19:55	13:20:10	<u>2 Hz</u>	10:25:08	10:25:23
<u>4 Hz</u>	13:20:30	13:20:45	<u>4 Hz</u>	10:25:43	10:25:58
<u>6 Hz</u>	13:21:05	13:21:20	<u>6 Hz</u>	10:26:18	10:26:33
<u>8 Hz</u>	13:21:40	13:21:55	<u>8 Hz</u>	10:26:53	10:27:08
<u>10 Hz</u>	13:22:15	13:22:30	<u>10 Hz</u>	10:27:28	10:27:43
Task C	13:24:45	13:28:15	Task B	10:29:58	10:33:28
<u>0 Hz</u>	13:25:05	13:25:20	<u>0 Hz</u>	10:30:18	10:30:33
<u>2 Hz</u>	13:25:40	13:25:55	<u>2 Hz</u>	10:30:53	10:31:08
<u>4 Hz</u>	13:26:15	13:26:30	<u>4 Hz</u>	10:31:28	10:31:43
<u>6 Hz</u>	13:26:50	13:27:05	<u>6 Hz</u>	10:32:03	10:32:18
<u>8 Hz</u>	13:27:25	13:27:40	<u>8 Hz</u>	10:32:38	10:32:53
<u>10 Hz</u>	13:28:00	13:28:15	<u>10 Hz</u>	10:33:13	10:33:28

Appendix E – Task Sequence Timing

<u>Task</u>	<u>Event</u>	<u>Start Time (s)</u>	<u>End Time (s)</u>	<u>Duration (s)</u>
Calibration				
	<u>Center Point</u>	0	3	3
	<u>Top</u>	3	6	3
	<u>Bottom</u>	6	9	3
	<u>Center</u>	9	12	3
	<u>Right</u>	12	15	3
	<u>Left</u>	15	18	3
	<u>Center</u>	18	20	2

<u>Task</u>	<u>Event</u>	<u>Start Time (s)</u>	<u>End Time (s)</u>	<u>Duration (s)</u>
Smooth Pursuit				
Vertical	<u>Center-Bot/Cent</u>	0	1.3	1.3
Horizontal	<u>Bot/Cent-Bot/Right</u>	1.3	2.5	1.2
Vertical	<u>Bot/Right-Top/Right</u>	2.5	5	2.5
Horizontal	<u>Top/Right-Top/Left</u>	5	7.5	2.5
Vertical	<u>Top/Left-Bot/Left</u>	7.5	10	2.5
Horizontal	<u>Bot/Left-Bot/Right</u>	10	12.5	2.5
Vertical	<u>Bot/Right-Mid/Right</u>	12.5	13.8	1.3
Horizontal	<u>Mid/Right-Center</u>	13.8	15	1.2

<u>Task</u>	<u>Event</u>	<u>Start Time (s)</u>	<u>End Time (s)</u>	<u>Duration (s)</u>
Visual Search				
	<u>Center</u>	0	2	2
	<u>Bot/Left</u>	2	3	1
	<u>Top/Mid</u>	3	4	1
	<u>Bot/Right</u>	4	5	1
	<u>Mid/Left</u>	5	6	1
	<u>Top/Right</u>	6	7	1
	<u>Bot/Mid</u>	7	8	1
	<u>Mid/Right</u>	8	9	1
	<u>Top/Left</u>	9	10	1
	<u>Center</u>	10	11	1
	<u>Bot/Left</u>	11	12	1
	<u>Mid/Right</u>	12	13	1
	<u>Bot/Right</u>	13	14	1
	<u>Center</u>	14	15	1

Appendix F - Test Checklist

Equipment Setup

- Ensure all cable connections are secure
 - BIOPAC to BIO computer
 - BIOPAC to EOG Leads
 - BIOPAC to Accel.
 - Battery to Camera/LED and Breadboard
 - Display VGA to DISP computer
 - Display USB to DISP computer
 - DVR to Camera
 - DVR to Hard Drive
- Turn on equipment
 - BIOPAC
 - DVR
 - Display
- Setup equipment for test
 - Ensure DVR is not recording yet
 - Ensure LED/Camera are functioning
 - Ensure that the BIOPAC is in correct settings
 - Upload Calibration and Test screen on DISP computer
 - Ensure that the display settings are for double screen
 - Ensure that Display is receiving input
 - Connect BIO computer to BIOPAC
 - Setup THREE channels for recording
 - CH 1- Horizontal
 - CH2- Vertical
 - CH3- Accel
 - Calibrate Accel.
 - Attach Accel. to bitebar
 - Create folder and subfolder for subject
 - Sub_XX\Test_X\Task_X

Subject Setup

- Subject fills out pre-test questionnaire
- Subject creates custom mouth guard for bitebar
- Brief subject on tasks, expectations of subject, safety
- Explain the equipment to subject
 - Check to make sure everything is working again
- Check to see what size helmet is needed for subject
- Seat subject in flight seat
- Lightly harness subject
- Place helmet on subject's head
- Ensure visor slides over the face
- Check for display to be visible to subject and working
- Check to see if the eye is properly aligned and illuminated with the camera
- Connect EOG leads using generous amounts of gel
- Secure wires so not to obstruct or distract subject vision
- Ensure that signal is being received by BIO computer
- Lower visor carefully so not to remove electrodes
- Insert mouth guard and attach Accelerometer
- Tighten up harness
- Give a final explanation/overview of tasks
- Ensure wiring and equipment is out of the way of the vibration table

Test Setup

- Start recording of EOG
- Start recording of DVR
 - Annotate start time for DVR recording
- Conduct test according to test matrix
- Drop Flag (F9) into data immediately upon each task beginning
- Stop EOG recording when task has finished
- Save EOG files individually after each task at each frequency
 - Sub_XX\Test_X\Task_X\XX_Hz.acq
- Open new EOG file upon saving previous file
- Repeat for each task and frequency condition

Post-Test

- Stop DVR recording
- Ensure EOG files have been saved
- Inform subject to wait until pressure has been turned off the table
- Remove harness, helmet and electrodes
- Direct subject to nearest sink to wash up
- Clean leads with warm water and Q-tip
- Subject fills out post-test questionnaire
- Backup eye recording files to Hard Drive
- Shut down all equipment

Data Processing

- Must export each individual EOG recording file from .acq to .xlsx
- Open EOG .acq file
- Click “File/Save as...”
- Select file type to save as: “.xlsx”
- Save file according to the following format”
 - Subject#-Test#-Frequency#-Task Letter
 - Example: 3-1-6-A.xlsx
 - Subject 3, Test 1 @ 6 Hz performing Fixation Task A
- Repeat for each .acq file
- Export all files to individual subject folders
- Ensure MATLAB’s path is set to individual subject folders
- Run each Task Analysis following prompt

Appendix G – MATLAB Code

```
%Task A Data Analysis%
%=====
format long

close all

clear

clc

%Input File Information

    fname=input('Enter File Name: ','s');

    Start = input('Start: ');

%Get File Size

    [length width] = size(fname);

%Get Frequency from File

    if width <= 7

        freq = fname(5);

    else

        freq =fname(5:6);

    end

    hz = str2num(freq);

%Read in .xlsx file

    data_1=xlsread(fname);

%Mark Start and End points

    Start = Start*1000;

    End = Start + 15000;

%Get appropriate time segment from data

    Time = data_1(Start:End,1);

    Horz = data_1(Start:End,2);

    Vert = data_1(Start:End,3);
```

```

data_1 = (horzcat(Time,Horz,Vert));

[length,width]= size(data_1);

%Moving Average

window = 250;

mask = ones(1, window)/window;

Mov_Avg = conv(Vert, mask, 'same');

%New Vertical Data subtracted Moving Average

Mov_Avg_Vert = Vert- Mov_Avg;

%Plot New Vertical

figure;

plot(Mov_Avg_Vert,'k');

xlabel('Time [ms]'); ylabel('Amplitude [mV]');

title('Moving Average Filtered Data WITH Segment Lines');

legend('Filtered Data @ 6Hz', 'Segment')

%Input sample limits

Start_Limit = input('Start Time for Limit: ');

End_Limit = input('End Time for Limit: ');

%Convert Limit input

Start_Limit = Start_Limit*1000;

End_Limit = End_Limit*1000;

%Max and min of sample

sample = Mov_Avg_Vert(Start_Limit:End_Limit);

Max_Limit = max(sample);

Min_Limit = min(sample);

%Run Moving Average Vertical through Filter

b =1;

```

```

        for a = 1:length-1

%Max Filter

            if Mov_Avg_Vert(a) <= Max_Limit*(3/4)

%Min Filter

                if Mov_Avg_Vert(a) >= Min_Limit*(3/4)

%Create New Filter

                    Final_Vert(b,:) = Mov_Avg_Vert(a);

                    b= b+1;

                end

            end

        end

end

%Size of Filtered Vertical Data

[length_new width_new] = size(Final_Vert);

%Create new time dimensions

Time_new = data_1(1:length_new,1);

%Concatenate Time and Vertical Data

data_1 = horzcat(Time_new,Final_Vert);

%Size of Data

[length width] = size(data_1);

%Start RMS Calculations

iChannelNum = 1; %# of channels

f1 = 1000;    %Sampling rate-Hz

dCutoff = 150; %Frequency cutoff-Hz

f2 = f1*2;

%Columns and Rows

iNumColumns = width;

iNumRows = length-1;

```

```
%Subtract Mean average of data
```

```
for i = 2:iNumColumns  
    data_1(:,i) = data_1(:,i) - mean(data_1(:,i));  
end
```

```
%Multiply in gravity
```

```
data_1 = data_1(2:iNumRows+1,1:iNumColumns);  
data_1(:,2:iNumColumns) = data_1(:,2:iNumColumns) .* 9.81;
```

```
%This function computes the rms using the linear PSD.
```

```
my_rms(1,1) = 0;  
my_rms(1,2:iNumColumns) = 1:iChannelNum';  
iNumPoints = ceil(dCutoff / 0.5) + 1;
```

```
%Calculate PSD with Welch's method
```

```
for i = 2:iNumColumns  
    signal = data_1(:,i);  
    signal = (signal - mean(signal));  
    ps = pwelch(signal, f2, f1, f2, f1);  
    my_rms(2:iNumPoints+1,i) = sqrt(ps(1:iNumPoints)*(f1 / f2));  
end  
fr = (0:iNumPoints-1)' * 0.5;  
my_rms(2:iNumPoints+1,1) = fr;
```

```
%Plot RMS vs Frequency
```

```
figure;  
plot(my_rms(2:iNumPoints+1,1),my_rms(2:iNumPoints+1,2),'k');  
xlabel('Frequency [Hz]'); ylabel('RMS');  
title('RMS vs Frequency for Vertical Eye Movement');  
legend('RMS', 'RMS @ 6 Hz')
```

```
%Find and output RMS information for sample
```

```

[x_lim,y_lim]=find(my_rms(:,1)==12);
[value] = find(my_rms(:,1) == hz);
[v,i]= max(my_rms(4:x_lim,2));
vert_rms_freq = my_rms(value,2)
vert_max_rms = my_rms(i+3,2)
Starttime=Start_Limit/1000
Endtime=End_Limit/1000
vert_FREQ_MAX= my_rms(i+3,1)
hz

```

```

%Task B Data Analysis%

%=====

format long

close all

clear

clc

%Input File Information

fname=input('Enter File Name: ','s');

Start = input('Start: ');

%Get File Size

[length width] = size(fname);

%Get Frequency from File

if width <= 7

    freq = fname(5);

else

    freq =fname(5:6);

end

hz = str2num(freq);

%Read in .xlsx file

data=xlsread(fname);

%Mark Start and End points

Start = Start*1000;

End = Start + 15000;

%Get appropriate time segment from data

Time = data(Start:End,1);

Horz = data(Start:End,2);

```

```

    Vert = data(Start:End,3);

%Create new data array

    data = (horzcat(Time,Horz,Vert));

    [length,width]= size(data);

%Cut horizontal segments data

    %BottomCenter-BottomRight

    BC_BR = Vert(1300:2500);

    %TopRight-TopLeft

    TR_TL = Vert(5000:7500);

    %BottomLeft-BottomRight

    BL_BR = Vert(10000:12500);

    %MiddleRight-Center

    MR_C = Vert(13800:15000);

%Combine segments

    Horz_Seg_Total=[];

    Horz_Seg_Total(1:1201,1) = BC_BR;

    Horz_Seg_Total(1202:3702,1) = TR_TL;

    Horz_Seg_Total(3703:6203,1) = BL_BR;

    Horz_Seg_Total(6204:7404,1) = MR_C;

    [length width] = size(Horz_Seg_Total);

%Moving Average

    window = 250;

    mask = ones(1, window)/window;

    Mov_Avg = conv(Horz_Seg_Total, mask, 'same');

%New Vertical Data subtracted Moving Average

    Mov_Avg_Horz_Seg = Horz_Seg_Total- Mov_Avg;

```

```

%Plot New Vertical

figure;

plot(Mov_Avg_Horz_Seg);

%Input sample limits

Sample_Start_time = input('Start Time for Limit: ');

Sample_End_time = input('End Time for Limit: ');

%Convert Limit input

Start_Limit = Sample_Start_time*1000;

End_Limit = Sample_End_time*1000;

%Max and min of sample

sample = Mov_Avg_Horz_Seg(Start_Limit:End_Limit);

Max_Limit = max(sample);

Min_Limit = min(sample);

%Run Moving Average Vertical through Filter

b = 1;

for a = 1:length-1

    %Max Filter

    if Mov_Avg_Horz_Seg(a) <= Max_Limit

        %Min Filter

        if Mov_Avg_Horz_Seg(a) >= Min_Limit

            %Create New Filter

            Final_Horz_Seg(b,:) = Mov_Avg_Horz_Seg(a);

            b = b+1;

        end

    end

end

end

```

%Size of Filtered Vertical Data

```
[length_new width_new] = size(Final_Horz_Seg);
```

%Create new time dimensions

```
Time_new = data(1:length_new,1);
```

%Concatenate Time and Vertical Data

```
data = horzcat(Time_new,Final_Horz_Seg);
```

%Size of Data

```
[length width] = size(data);
```

%Start RMS Calculations

```
iChannelNum = 1; %# of channels
```

```
f1 = 1000; %Sampling rate-Hz
```

```
dCutoff = 150; %Frequency cutoff-Hz
```

```
f2 = f1*2;
```

%Columns and Rows

```
iNumColumns = width;
```

```
iNumRows = length-1;
```

%Subtract Mean average of data

```
for i = 2:iNumColumns
```

```
data(:,i) = data(:,i) - mean(data(:,i));
```

```
end
```

%Multiply in gravity

```
data = data(2:iNumRows+1,1:iNumColumns);
```

```
data(:,2:iNumColumns) = data(:,2:iNumColumns) .* 9.81;
```

%This function computes the rms using the linear PSD.

```
my_rms(1,1) = 0;
```

```
my_rms(1,2:iNumColumns)= 1:iChannelNum';
```

```

iNumPoints = ceil(dCutoff / 0.5) + 1;

%Calculate PSD with Welch's method

for i = 2:iNumColumns

    signal = data(:,i);

    signal = (signal - mean(signal));

    ps = pwelch(signal, f2, f1, f2, f1);

    my_rms(2:iNumPoints+1,i) = sqrt(ps(1:iNumPoints) * f1 / f2);

end

fr = (0:iNumPoints-1)' * 0.5;

my_rms(2:iNumPoints+1,1) = fr;

%Plot RMS vs Frequency

figure;

plot(my_rms(2:iNumPoints+1,1),my_rms(2:iNumPoints+1,2));

xlim([0 12]); ylim([0,.1]);

xlabel('Frequency [Hz]'); ylabel('RMS');

title('RMS vs Frequency for Horizontal Segments');

%Find and output RMS information for sample

[x_lim,y_lim]=find(my_rms(:,1)==12);

[value] = find(my_rms(:,1) == hz);

[v,i]= max(my_rms(4:x_lim,2));

RMS_Freq = my_rms(value,2)

Max_RMS = my_rms(i+3,2)

Sample_Start_time

Sample_End_time

Freq_max= my_rms(i+3,1)

```

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14. ABSTRACT HMDs and their integration into military systems have greatly improved. However, a significant issue with HMDs is the effect of vibration and the Vestibulo-Ocular Reflex (VOR). When a human's head is subject to low-frequency vibration, the VOR stabilizes the eye with respect to the external environment. However this response causes blurring of an HMD display as the system moves with the user's head. This research sought to understand the VOR as a function of whole body low-frequency vibration. An experimental HMD was developed to allow a user to perform visual tasks, while also recording eye movements via video recording and EOG. A human subject experiment was executed to collect data on vibration effects on eye movement while performing tasks chosen to isolate specific eye motions. The results indicate that during fixation on a stationary target, the magnitude of eye movement was greatest at 4-6 Hz. The addition of motion to this target significantly increased the magnitude at this range. The findings are consistent with previous research which has found a decline in visual performance at 4-6 Hz.					
15. SUBJECT TERMS Vestibulo-Ocular Reflex, VOR, Helmet-Mounted Display, HMD, Vibration					
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